KATHOLIEKE
UNIVERSITEIT
LEUVEN

DEPARTEMENT TOEGEPASTE ECONOMISCHE WETENSCHAPPEN

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ANALYZING AND IMPROVING NETWORK PUNCTUALITY AT A BELGIAN AIRLINE COMPANY USING SIMULATION

by
J. ADEM
J. MARTENS

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Analyzing and Improving Network Punctuality at a Belgian Airline Company using Simulation

Adem J., Martens J.
Katholieke Universiteit Leuven
Faculty of Economics and Applied Economics
Naamsestraat 69
3000 Leuven, Belgium

Abstract

This research report covers the results of a study that we carried out to investigate the effect of possible improvement strategies to boost the punctuality of a Belgian airline company. The study was carried out in two parts. First, we analyzed the performance of an existing airline network. Research targets that were set for this part included a disclosure of the most important delay reasons, insight into the performance of airports in the network, a verification of the presence of any propagation of delay, etc. In a second part, we built a simulation model to evaluate several strategies to improve the network punctuality. In that respect, we developed a preliminary version of a user friendly simulation environment to analyze the impact of published block times, aircraft swapping rules, spare aircraft availability and other factors on the punctuality. We built a template in the simulation package ARENA, that allows for a quantitative punctuality evaluation of a particular network proposal. The ARENA template allows the user to construct any network of choice with an unlimited number of carriers, flights and line stations and returns a number of useful output measures enabling the user to validate the quality of his particular network proposal.

Keywords: Simulation, Airline Network, Punctuality

Introduction

Achieving a punctual flight scheme is one of the key factors for success in modern airline companies. High competition and an imbalanced supply/demand relationship makes an adequate *quality of service* (that includes *punctuality*) indispensable to survive. Indeed, a punctual network is one of those convincing arguments that airline companies may produce to win over customers to fly with them. Punctuality however depends on many factors as there are air space congestion, performance of airports, airline network design, etc. It is then only natural to ask which of these influencing factors returns the most favorable (and affordable!) rise in punctuality. In that respect, it lies within the aim of this study to investigate the current punctuality status at a major Belgian airline company and to search for and evaluate possible network punctuality improvement scenarios. In the remainder of the text, because of the confidentiality of the data, we will refer to the Belgian company as *BelgoPunc.*

With regard to the method of network evaluation, we opt for *simulation.* In that view, we developed a simulation environment within the popular simulation package ARENA that can be used to simulate any network of choice with an unlimited number of carriers, flights and line stations. The output of the simulation model covers statistics such as line station performance, number of departures/arrivals on time, swapping activity, etc. Ultimately, the simulation model can be used to instantly verify the expected punctuality of a particular network proposal.

The content of this research report is organized in two parts. Part I contains an extensive coverage of the current punctuality status at *BelgoPunc.* After a short introduction to the well-known hub & spoke architecture in the airline industry, we will focus mainly on an analysis of data that was provided by *BelgoPunc.* Topics include a block time & turnaround analysis of the flights and line stations included in *BelgoPunc's* network, a study of swapping behavior, propagation of delay, etc. Part II is then completely focussed on the simulation model and the obtained simulation results. We will address the modelling framework that we followed and discuss some of the modelling choices that we made. Also, a short discussion of some implementation aspects is provided. The second part is concluded with an elaborate treatment of various punctuality improvement scenarios and their estimated punctuality gain by simulation. The research report is ended by formulating some ideas for future research.

Part I
Punctuality at a Belgian Airline Company

1 Airline Industry Fundamentals

1.1 Hub and Spoke Architecture

At the heart of today's airline industry lies the well-known *hub and spoke* architecture. The hub and spoke model is the result of the deregulation of the airline industry in the last decades and basically enables airline companies to serve more markets, to achieve higher load factors and hence to reduce their unit-operating costs. A hub is a strategically located airport that acts as a transfer point for passengers that are moving from one community to another. Other airports form satellite line stations that organize daily flights to and from the hub. A typical snapshot of a time table of incoming and outgoing flights at a hub is pictured in figure 1. The figure shows part of the morning peak in *BRU* (Brussels, the hub). As can be seen from the figure, an incoming carrier *CAR_1* with flight number *MA200* is scheduled to arrive at 8:20 at the hub (8:20 is also referred to as the *scheduled time of arrival* or *STA*). A time period of 50 minutes is reserved for rotating the carrier and preparing it for its next flight *MA405*. The time frame of 50 minutes is called the *turn around time* or *TAT*. The process of rotating a carrier consists of unloading the passengers and the luggage from the aircraft, cleaning and refueling the plane, boarding new passengers, etc. The time at which the carrier is scheduled to leave is labeled as the *scheduled time of departure* or *STD*. Notice that in approximately the same time frame, two other carriers *CAR_2* and *CAR_3* are scheduled to arrive, giving passengers the opportunity to jump from one carrier to another in order to reach their destination.

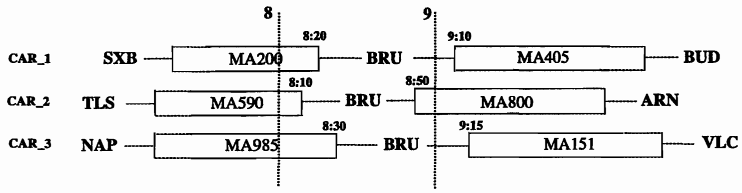

Figure 1: Incoming and Outgoing Flights at a Hub Station

Usually, a flight table consists of many carriers of the same type that perform several flights daily (the flight plan for an aircraft is also called a *rotation*). The flights are connections between the hub and a line station. It is not uncommon that a rotation contains 6 to 8 flights. To maximize the possibility for passengers to jump from one plane to another in order to reach their destination, the flights are organized such that the majority of the aircraft pass the hub in approximately the same time frame. For *BelgoPunc's* network part that we consider in this report, it turns out that flights are organized such that 3 *peaks* of incoming/departing flights arise at the hub: an early morning peak, an afternoon peak and an evening peak. The entire set of line stations, interconnected flights and the hub form a *hub & spoke architecture* and will also constitute the frame of reference for our simulation model.

1.2 Flight Delays and Network Design

Most of todays commercial airline companies face many delays in their published time table. It is not uncommon for an airline company to see up to 40% or more of its flights being delayed at departure. The most commonly used delay thresholds in practice are the 3-minute norm and the AEA norm of 15 minutes. Depending on the fleet, fuel prices, crew wages and other factors, the yearly cost of delays may grow well over 4 billion EURO [IATA] for the European airline market. Some of these departure delays may be due to a late arrival of an incoming carrier, others may be caused by bad weather conditions, late boarding of passengers, local air traffic congestion, technical problems, connection difficulties, or just bad network design. A complete list of delay reasons and their codes as they are documented by [IATA] is given in the appendix. The simulation model that we will develop in a later section also makes use of this list of delay codes.

Some of the delays are a direct consequence of poor network design. Frequent rotational delays, which are caused by a late arrival of an incoming carrier, is a typical indication of a shortcoming in the network design. In that case, one might have to increase the *block time*[1] or widen the scheduled *turnaround time*. Other delays are directly related to the turnaround performance of a line station. Recurrent boarding delays may be a sign of a low productive line station. Notice that delays can be outside the influencing area of an airline company. Although debatable, ATC Flow, a departure delay that is caused by air traffic congestion on the route to the destination, is in that respect often considered as an exogenous delay. In cooperation with *BelgoPunc*, we classified the delay list of the appendix into *endogenous* and *exogenous* delays as follows:

ENDOGENOUS	01,09,11,12,13,14,15,16,17,18,21,22,23,24,25,26,27,28,29,31 32,33,34,35,36,37,38,39,41,42,43,44,45,46,47,48,52,55,56,57 58,61,62,63,64,65,66,67,68,69,75,87,91,92,94,95,96,97,99
EXOGENOUS	51,71,72,73,76,77,81,82,83,84,85,88,89,98
OTHER	02,40,93

Table 1: Endogenous & Exogenous Delay Reasons

In any case, it is clear that statistics on flight delays form one of the key inputs in a network design process and hence in our simulation model. Other major components include flying time statistics, turnaround performance data of line stations, market related flight statistics, crew availability, fleet information and details on interconnected flights. Not all of these components have yet been completely implemented in our simulation model and some remain the topic for future research activities.

[1]The *block time* includes the time it takes the aircraft to taxi to the runway, the flying time and the time to taxi to the gate at the arrival station.

2 Punctuality Study

In the following paragraphs, we will present the major findings of our study of the network punctuality at *BelgoPunc*. Topics that we will discuss include the frequency of delays, the distribution of endogenous & exogenous delay reasons, the performance of line stations, swapping behavior at the hub, etc. The study provides us also with a useful insight into possible modelling strategies of some of the airline's industry key processes (e.g. *turnaround*). It may be worthwhile for the reader to consult figure 1 again as we intend to present our results in a "chronological" order, starting with the first flights on a day.

2.1 Data Model

The data that we received from *BelgoPunc* covers a collection of inter-European flights in the 1999 summer season, running from the 28th of March till the 30th of October. In total, there were 28 rotations (and hence 28 carriers), summing up to 188 flights that were carried out each day. A total of 35 line stations are included in the network. The data contains numerous information on flights and carriers, among which the most important data fields are (for each flight per day): (1) the flight number *(MAxxx)*, (2) the carrier *(CAR_x)*, (3) the scheduled time of departure *(STD)*, (4) the actual time of departure *(ATD)*, (5) a pair of delay reasons and delay lengths at departure *(DR1, DR2, DL1, DL2)*, (6) the scheduled time of arrival *(STA)* and (7) the actual time of arrival *(ATA)*. For flights that pass through the hub, (8) a registration number *(REGxxx)* is also recorded which gives us the opportunity to track a potential swapping of carriers at the hub.

2.2 Early Morning Departures

An *early morning departure (EMD)* is the first flight on a day in a particular rotation. For every line station that performed *EMD* flights in the 1999 summer schedule, we made a histogram of the departure delay.[2] To give an example, consider the histogram of the delay of the early morning flight *MAxxx* at Glasgow airport *(GLA)*, as depicted in figure 3 (which is based on 215 observations). The image of frequent delays as pictured in figure 3 is typical for many line stations. The reader is invited to consult the appendix where an overview of the histograms of all *EMD* flights in *BelgoPunc's* network is given.

[2]The histogram is built such that the upper bound of a class is also part of that class.

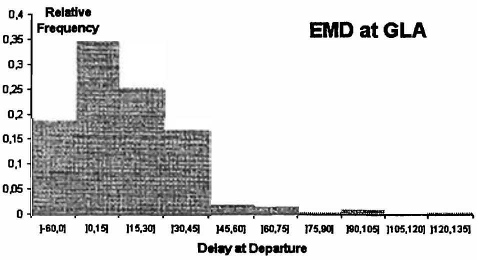

Figure 2: Delay at Departure of EMD Flight in Glasgow

In the table below, we show for each line station the percentage of *EMD* flights that took place without incurring a delay.[3] Notice that *BRU* was not given a rank because it is the hub station of *BelgoPunc*. We added its value anyway for comparative reasons. To gain some insight into the geographical spread of *EMD* delays, a map was made. Only those line stations that perform an *EMD* flight are shown. The 50 % worst operating line stations for the statistic *% departures before or on STD* are marked in gray.

STATION	% ON TIME	RANK
THF	63,3%	1
BRU	51,3%	
DUS	51,1%	2
CPH	46,4%	3
BUD	44,9%	4
HAJ	44,9%	5
BOD	41,9%	6
TLS	35,3%	7
NCL	30,7%	8
TRN	27,3%	9
HAM	24,2%	10
MRS	20,5%	11
SXB	19,5%	12
GLA	18,6%	13
EDI	17,7%	14
NAP	15,8%	15
LBA	15,3%	16
BHX	12,4%	17
FLR	12,3%	18
LCY	9,9%	19
BRS	8,2%	20

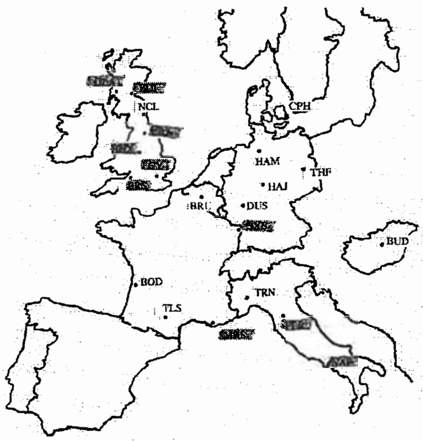

Table 2: EMD Performance of Line Stations

As we mentioned yet earlier, endogenous delay reasons are considered to fall under direct control of the line station itself. The aim of the table below is to see how frequently delays were caused by endogenous and by exogenous factors. The line stations appear in order of their rank. Line stations having 85% or more of their reasons caused by exogenous factors are indicated in light gray on a small map. The other line stations are marked in dark gray. In order to gain some insight into the main exogenous reasons for each line station, we constructed table 4. The table lists the most frequent exogenous delay reasons together with their share in the pool of all exogenous delay reasons that occurred at the line station. Again, the line stations are ordered according to the rank. From left to right, reasons are indicated in bold until the cumulative percentage exceeds the value of 80%. For comparative reasons, we also included the results for *BRU*. The reader is encouraged to consult the appendix for an explanation of the delay codes.

[3]This percentage corresponds to the relative frequency of the first class in the histograms.

STATION	% ENDO	% EXO	OTHER
THF	33,5%	66,5%	0,0%
BRU	28,9%	65,2%	5,9%
DUS	19,9%	80,1%	0,0%
CPH	27,6%	71,3%	1,1%
BUD	8,8%	87,9%	3,3%
HAJ	69,6%	29,2%	1,2%
BOD	53,2%	46,8%	0,0%
TLS	32,2%	61,9%	5,9%
NCL	9,6%	90,4%	0,0%
TRN	9,6%	90,4%	0,0%
HAM	28,5%	68,1%	3,4%
MRS	37,0%	61,1%	1,4%
SXB	25,3%	73,7%	1,0%
GLA	19,3%	79,5%	1,2%
EDI	22,0%	77,5%	0,5%
NAP	5,1%	93,9%	1,0%
LBA	8,1%	90,7%	1,2%
BHX	3,0%	93,4%	3,6%
FLR	38,8%	61,2%	0,0%
LCY	4,9%	92,2%	2,9%
BRS	4,8%	95,2%	0,0%

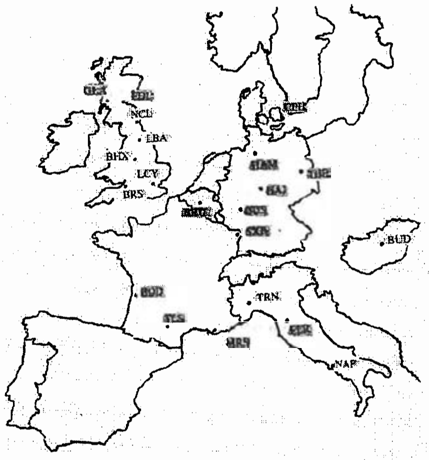

Table 3: Exogenous & Endogenous Delay Reasons at EMD Line Stations

Tables 2 till 4 show that punctuality performance for *EMD* flights differs significantly among the line stations. The percentage of departures before or on *STD* varies from 8,2% to 63,3%. Some of the line stations are much more inflicted with endogenous reasons than others. Also, the reasons why an airplane departs too late vary strongly, although, looking at the exogenous delays, most stations seem to suffer from typical congestion delays (like 81, 88 and 89). In any case, it is clear from an intuitive point of view that in order to obtain a satisfying level of network punctuality, the number of late *EMDs* should be kept at a minimum level. The target of achieving punctual *EMD* flights is endorsed by *BelgoPunc's* practice as the company fears that late *EMDs* may give rise to a "snowball" effect which causes an early morning delay to propagate throughout an entire rotation! We will look into this matter of delay propagation further in paragraph 2.6. Since exogenous reasons do not fall directly under control of a line station, one cannot held a station directly accountable for delays due to exogenous reasons. This suggests specific targets or *service level agreements* should be agreed upon with each line station deciding on a maximum allowed share of *endogenous* delay reasons in the total pool of (both endogenous and exogenous) delay reasons they incur in a season. Preventing the occurrence of *exogenous* reasons becomes then basically a matter of adequate *network design*.

THF	81 (59%)	88 (25%)	85 (8%)	72 (8%)				
BRU	89 (46%)	81 (31%)	82 (14%)	84 (5%)	83 (1%)	88 (1%)	71 (1%)	72 (1%)
DUS	84 (43%)	89 (39%)	82 (18%)					
CPH	88 (50%)	72 (23%)	81 (15%)	89 (7%)	84 (3%)	82 (2%)		
BUD	81 (69%)	88 (24%)	72 (5%)	89 (2%)				
HAJ	84 (24%)	81 (24%)	72 (24%)	88 (20%)	89 (8%)			
BOD	81 (38%)	88 (36%)	72 (18%)	89 (4%)	98 (2%)	82 (2%)		
TLS	81 (23%)	88 (22%)	72 (22%)	89 (17%)	84 (11%)	82 5(%)		
NCL	88 (44%)	81 (40%)	72 (14%)	89 (2%)				
TRN	81 (71%)	89 (11%)	72 (9%)	88 (8%)	83 (1%)	71 (1%)		
HAM	81 (40%)	88 (27%)	82 (18%)	72 (9%)	89 (4%)	84 (1%)	71 (1%)	
MRS	81 (59%)	88 (14%)	82 (10%)	72 (9%)	84 (4%)	89 (2%)	83 (2%)	
SXB	81 (86%)	72 (8%)	88 (5%)	89 (1%)				
GLA	81 (46%)	88 (35%)	72 (14%)	89 (2%)	83 (2%)	82 (1%)		
EDI	81 (43%)	88 (27%)	89 (14%)	84 (9%)	72 (9%)			
NAP	81 (53%)	88 (27%)	72 (12%)	89 (7%)	71 (1%)			
LBA	88 (46%)	81 (36%)	72 (12%)	89 (3%)	71 (1%)	82 (1%)	77 (1%)	
BHX	81 (45%)	88 (40%)	72 (9%)	89 (5%)	85 (1%)			
FLR	81 (43%)	89 (24%)	88 (17%)	72 (9%)	83 (5%)	82 (1%)	51 (1%)	
LCY	81 (57%)	88 (28%)	89 (13%)	84 (1%)	72 (1%)			
BRS	88 (51%)	81 (29%)	72 (12%)	83 (6%)	89 (1%)	84 (1%)		

Table 4: Main Exogenous Delay Reasons of EMD Flights

2.3 Block Time Analysis

The *block time (BT)* is the time it takes the aircraft to taxi to the runway, the flying time and the time to taxi to the gate at the arrival station. For each flight in the summer 1999 schedule, a cumulative distribution of the realized block times was made. Figure 3 illustrates this plot for a flight from *NCL* (Newcastle) to *BRU* (Brussels), of which the block time was scheduled to be 80 minutes (the plot is based on 215 observations).

As can be seen from the figure, only half of the flights were performed within a time frame equal to or smaller than the scheduled block time. The cumulative frequency that corresponds to the scheduled *BT* is also called the *coverage*. In that respect, the flight from figure 3 is said to have a coverage of 50%. Notice that the block time behavior of figure 3 is not a stand-alone phenomenon. As a matter of fact, for many flights of *BelgoPunc's* network (including the *EMD* flights from the previous paragraph), coverages are found at or below the level of 50% (see also figure 4). The reason for such low coverages is basically *commercial*. Indeed, by setting the block time at a low level, an airline company can outperform the competition as they offer faster connections (on paper!) between line stations. It requires little argumentation to see that the implications of low coverages include late arrivals, rushed circumstances at line stations, and inevitably a decline in departure punctuality.

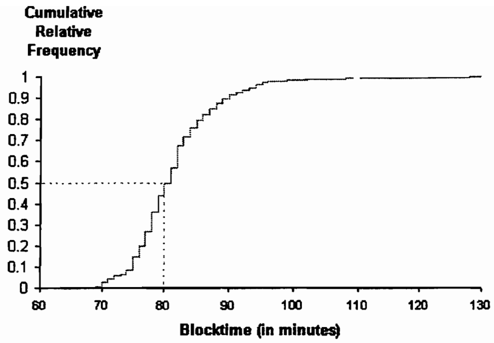

Figure 3: Cumulative Distribution of Block Times of a Flight

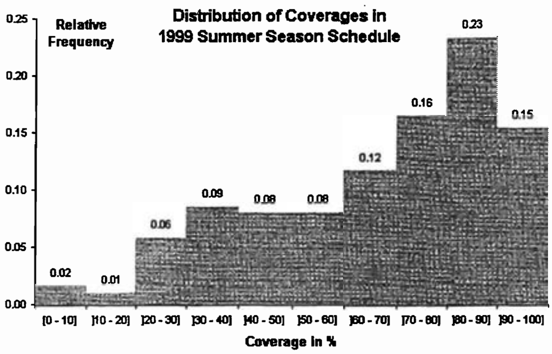

Figure 4: Distribution of BT Coverages in the Summer 1999 Schedule

2.4 Turnaround Analysis

2.4.1 Overview

Once a carrier has arrived at a line station, it needs to be prepared for its next flight. Analyzing the 1999 summer schedule data, we found it useful to identify a number of different "turnaround scenarios" that can occur at a line station. These scenarios are illustrated in figure 5. Let the pair (i, o) stand for an incoming flight i and an outgoing flight o. Three cases are identified by figure 5:

- (1) the incoming plane is on time ($ATA_i \leq STA_i$): turnaround proceeds according to normal circumstances.
- (2) the incoming aircraft is late ($STA_i < ATA_i \leq STD_o - NORM$), turnaround proceeds according to agitated circumstances. *NORM* refers to a target *TA* time that should be sufficient for rotating an aircraft. See also the following paragraph.

- (3) the incoming plane has considerable delay such that there is normally insufficient time left to rotate the carrier in order to get the plane on time in the air for the next flight ($ATA_i > STD_o - NORM$), turnaround proceeds according to rushed circumstances.

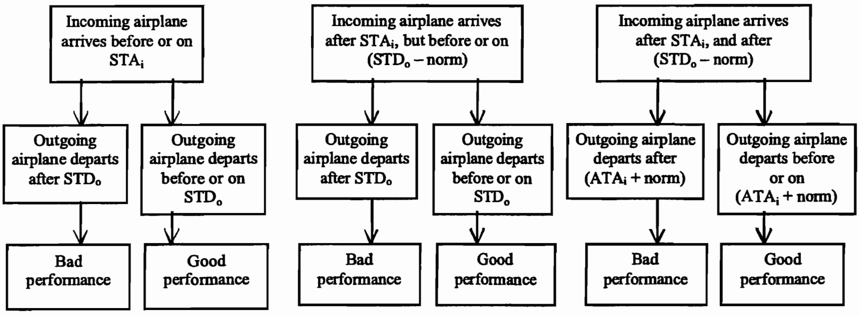

Figure 5: Arrival/Departure Scenarios at a Line Station

Notice carefully how the target for a line station is determined by the arrival situation of the incoming aircraft. In cases (1) and (2), the line station, if it operates adequately, should be able to put the carrier in the air before or on the flight's *STD*. In case (3) however, because of the considerable arrival delay of the incoming flight, the line station is expected to perform a *TA* in a time span no more than the *NORM*, i.e. it should be able to put the carrier in the air before or on $ATA_i + NORM$. This difference in targets is also illustrated in figure 6. The horizontal axis represents the arrival situation of the incoming flight. On the vertical axis, we put the *TA* time additional to the *NORM* that was needed for rotation at the line station. Notice how the first and the third quadrant correspond to the arrival cases (1) and (2). The second and the fourth quadrant correspond to case (3). Observation points that are on or below the bold line in the figure are observations of good performance (i.e. target reached).

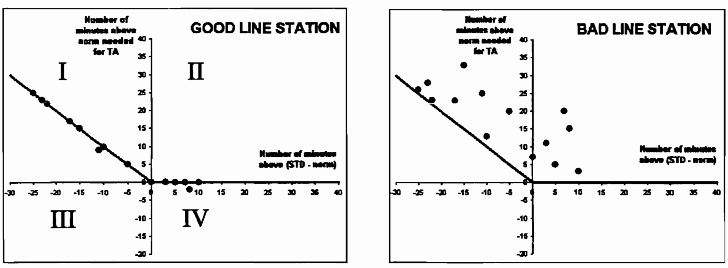

Figure 6: Productive and Non-Productive Line Stations

2.4.2 Determining the NORM

In order to derive the amount of time that should be sufficient to perform a turnaround of an aircraft, we separated turnaround activities at the hub (Brussels) from turnaround activities at other line stations. The reason for this separation boils down to the larger set of activities that need to be performed at the hub (e.g. refueling). Also, as the hub receives many more incoming flights in a limited time frame (a peak), it is only reasonable to provide it with more turnaround time than a line station. In order to quantify the NORM, all flights that arrived in a line station after the *STD* of the next flight (so flights for which holds that $ATA_i \geq STD_o$) were set apart. For these flights, realized turnaround times calculated as $ATD_o - ATA_i$ accurately reflect the amount of time that is spent *completely* on rotating the aircraft. Taking other cases as well (for which $ATA_i < STD_o$) would result in a blurring effect where the derived turnaround times would include a portion of time an aircraft is ready for its next flight but is just waiting for its *STD* to arrive. After elimination of the observations with missing values and swapped aircraft (for the hub), we were left with 265 useful observations for Brussels and 1516 for all other line stations. In order to withhold sufficient data points for all cases in figure 5, we decided to determine the *NORM* for *all* line stations instead of deriving a *NORM* for every line station *individually*. This provides us with a cumulative relative frequency plot of all *TATs* for Brussels and the other line stations, as is pictured in figure 7.

To set a value for both the *NORM* at the hub and a line station ($NORM_{HUB}$ & $NORM_{LS}$), it was decided, in agreement with *BelgoPunc* to use the 20% percentile of the realized *TAT* curve. For Brussels, the 20% percentile is 42 minutes. Since it is standard practice to work and think in time frames composed of 5 minute intervals, we set the $NORM_{HUB}$ at 40 minutes.[4] For the line stations, the 20% percentile lies at 27 minutes. Rounding off again, we choose to set the $NORM_{LS}$ at 30 minutes. In the remainder of the text, we will continue to employ the general term *NORM* to designate both $NORM_{HUB}$ and $NORM_{LS}$. The context will make it clear which of the two *NORMs* is meant.

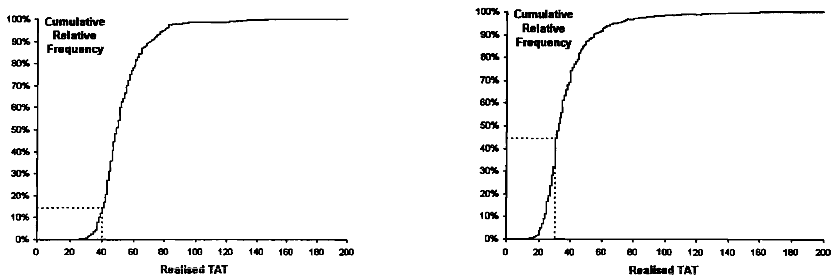

Figure 7: Cumulative Distribution of TAT in BRU and Other Line Stations

[4] Notice that as little as 14,34% of the realized *TATs* under rush circumstances fall within 40 minutes!

2.4.3 Evaluating Line Station Performance with the NORM

For each line station we constructed a scatter plot (like in figure 6) that summarizes the line station's *TA* performance. The scatter plots can be found in the appendix. Returning to figure 5 of the previous paragraph, we find 3 different arrival situations can occur for an airplane in a line station. Each of these 3 situations gives rise to two possible outcomes of *TA* performance: "good performance" and "bad performance". In table 5, we show how frequently a line station exhibits "good performance" for each of the three different arrival situations (%G column). The column N stands for the number of observations available to calculate the ratio. The line stations appear in order of best performance.

It is interesting to investigate whether any correlation is present between the performance ratios across the arrival scenarios. Table 5 displays the correlation between the ranking position (R) of the stations across the different arrival cases. For those line stations that had an *EMD* flight, a correlation between the *EMD* rank and the ranks of table 5 was also calculated. Based on the correlation values in table 5 we decided to make up a *single* ranking of line stations according to the percentage of time they exhibit good performance (see table 6).

2.4.4 Analyzing Turnaround Performance

It is worth to emphasize that the delay reason analysis that we are about to discuss is not strictly "compatible" with the above performance analysis. According to the performance analysis, an airplane that arrives at a line station before $STD - NORM$, is expected to leave at *STD*. Assume that it leaves 5 minutes after *STD* and that it had a delay of 10 minutes at arrival. Although according to figure 5, the *TA* performance of the line station is not good, it is in practice (looking at the data file of *BelgoPunc*) impossible to unravel for what reason because the delay at departure will be attributed to a so-called *rotational delay* (delay code 93). From the viewpoint of our performance analysis, delay code 93 would however not be allowed here as, according to the concept of the *NORM*, the line station had sufficient turnaround time left to rotate the aircraft. The reason why the two analyses are not compatible has to do with the fact that the persons that assign the delay codes in practice do not use the frame of reference as presented in figure 5. Nevertheless, an analysis of delay codes is useful because it can display what delay reasons are likely to occur in a line station. It is also our intention to employ this information in the simulation model to simulate reasons for delays at departure (see part II).

For each delay that occurred in the summer 1999 schedule, one or two delay reasons are given. The delay reasons were again subdivided into three subsets: endogenous, exogenous and other reasons as described previously. The aim of the table given below is to see what percentage of the delays was caused by endogenous and what percentage was caused by exogenous factors. The line stations appear in order of their rank. Leaving out the category of other reasons, line stations having 85% or more exogenous reasons are indicated in light gray. Line stations with less than 85% exogenous reasons are indicated in dark gray. We summarized the main exogenous delay reasons for each line station in table 8.

$ATA_i \leq STA_i$				$STA_i < ATA_i \leq STD_o - NORM$				$ATA_i > STD_o - NORM$			
LS	**%G**	**N**	**R**	**LS**	**%G**	**N**	**R**	**LS**	**%G**	**N**	**R**
ARN	93,3%	45	1	**ORY**	82,5%	274	1	**GOT**	83,3%	72	1
GOT	89,3%	121	2	**ARN**	78,4%	37	2	**ARN**	78,0%	41	2
ORY	87,7%	106	3	**GOT**	78,0%	59	3	**BIO**	76,8%	164	3
BIO	87,5%	8	4	**BHX**	73,7%	243	4	**BHX**	74,6%	197	4
THF	86,7%	120	5	**CDG**	73,7%	76	5	**SXB**	71,8%	124	5
CDG	85,7%	7	6	**THF**	67,2%	174	6	**ORY**	65,0%	137	6
BHX	84,8%	33	7	**HAJ**	66,5%	233	7	**BFS**	62,5%	16	7
HAJ	77,9%	86	8	**BRS**	60,1%	138	8	**TLS**	62,0%	308	8
LBA	77,0%	161	9	**LBA**	59,0%	212	9	**DUS**	60,2%	196	9
CPH	72,0%	182	10	**DUS**	58,6%	382	10	**CDG**	60,0%	55	10
BRS	66,8%	187	11	**BFS**	57,3%	75	11	**LBA**	59,1%	110	11
BFS	66,7%	27	12	**BIO**	57,1%	14	12	**AMS**	58,8%	364	12
PRG	64,4%	118	13	**SXB**	55,5%	137	13	**BRS**	58,1%	160	13
BUD	62,4%	85	14	**CPH**	50,6%	158	14	**THF**	54,9%	226	14
SXB	60,0%	50	15	**PRG**	48,1%	133	15	**NCL**	53,9%	219	15
GLA	57,1%	140	16	**BOD**	36,4%	11	16	**BOD**	53,7%	335	16
NCL	56,4%	94	17	**NCL**	33,9%	183	17	**HAJ**	51,9%	52	17
BOD	52,6%	19	18	**MRS**	33,3%	6	18	**CPH**	50,5%	366	18
NAP	50,0%	34	19	**NCE**	33,3%	51	19	**MUC**	46,4%	181	19
NCE	50,0%	4	20	**AMS**	29,3%	283	20	**STR**	39,1%	248	20
GVA	45,5%	22	21	**STR**	29,2%	65	21	**LYS**	33,9%	348	21
LYS	43,2%	132	22	**HAM**	26,4%	125	22	**PRG**	33,0%	182	22
TLS	41,4%	58	23	**GLA**	26,2%	61	23	**HAM**	26,7%	150	23
STR	40,8%	184	24	**NAP**	21,6%	37	24	**TRN**	25,3%	186	24
HAM	36,2%	94	25	**MUC**	18,8%	16	25	**BLQ**	25,3%	296	25
DUS	35,6%	250	26	**TRN**	18,7%	107	26	**GLA**	21,0%	162	26
MUC	31,7%	60	27	**BRU**	18,6%	1543		**FLR**	20,4%	431	27
BRU	28,6%	1963		**BUD**	17,2%	29	27	**BRU**	18,5%	2062	
AMS	25,7%	175	28	**GVA**	17,0%	141	28	**MRS**	17,8%	73	28
BLQ	25,7%	101	29	**LYS**	11,4%	35	29	**NCE**	11,8%	153	29
MRS	25,0%	4	30	**FLR**	11,1%	63	30	**BUD**	4,3%	47	30
TRN	17,5%	40	31	**BLQ**	0,0%	1	31	**GVA**	3,8%	52	31
FLR	13,0%	23	32	**TLS**	-	0		**VLC**	3,7%	190	32
VLC	4,0%	25	33	**VLC**	-	0		**NAP**	0,0%	82	33

	EMD RANK	RANK 1	RANK 2	RANK 3
EMD RANK	1	0,12	0,10	0,01
RANK 1	0,12	1	0,81	0,64
RANK 2	0,10	0,81	1	0,75
RANK 3	0,01	0,64	0,75	1

Table 5: Turnaround Performance of Line Stations & Correlations between Rankings

	%G	N	R
GOT	84,9%	252	1
ARN	83,7%	123	2
ORY	78,9%	517	3
BIO	75,8%	186	4
BHX	74,8%	473	5
CDG	68,8%	138	6
HAJ	67,1%	371	7
THF	66,4%	520	8
LBA	65,0%	483	9
SXB	62,7%	311	10
BRS	62,0%	485	11
BFS	60,2%	118	12
TLS	58,7%	366	13
CPH	56,1%	706	14
BOD	53,1%	365	15
DUS	52,0%	828	16
NCL	47,0%	496	17
PRG	46,2%	433	18
AMS	41,6%	822	19
MUC	41,2%	257	20
STR	38,4%	497	21
BUD	37,3%	161	22
GLA	35,8%	363	23
LYS	34,8%	515	24
HAM	29,0%	369	25
BLQ	25,3%	398	26
TRN	22,2%	333	27
BRU	22,1%	5568	
MRS	19,3%	83	28
FLR	18,9%	517	29
NCE	17,8%	208	30
GVA	16,7%	215	31
NAP	16,3%	153	32
VLC	3,7%	215	33

Table 6: TA Performance of Line Stations: Final Ranking

	% ENDO	% EXO	% OTHER
GOT	11,1%	33,3%	55,6%
ARN	5,4%	10,8%	83,8%
ORY	12,3%	36,5%	51,2%
BIO	1,8%	4,3%	93,9%
BHX	8,8%	27,2%	64,0%
CDG	15,3%	22,6%	62,1%
HAJ	31,2%	23,7%	45,1%
THF	8,2%	20,1%	71,7%
LBA	6,5%	46,1%	47,4%
SXB	5,8%	28,9%	65,3%
BRS	8,2%	41,8%	50,0%
BFS	7,7%	69,2%	23,1%
TLS	10,9%	15,6%	73,5%
CPH	10,6%	27,9%	61,5%
BOD	9,4%	14,0%	76,6%
DUS	9,4%	47,9%	42,7%
NCL	6,5%	36,5%	57,0%
PRG	2,3%	32,2%	65,5%
AMS	22,3%	38,7%	39,0%
MUC	4,2%	36,6%	59,2%
STR	5,6%	35,8%	58,6%
BUD	7,4%	40,6%	52,0%
GLA	16,7%	29,5%	53,8%
LYS	7,2%	39,3%	53,5%
HAM	20,6%	21,6%	57,8%
BLQ	2,5%	47,7%	49,8%
TRN	2,1%	60,2%	37,7%
BRU	20,4%	49,6%	30,0%
MRS	3,4%	34,0%	62,6%
FLR	5,2%	40,8%	54,0%
NCE	3,7%	29,6%	66,7%
GVA	3,4%	19,2%	77,4%
NAP	5,3%	33,9%	60,8%
VLC	29,5%	17,8%	52,7%

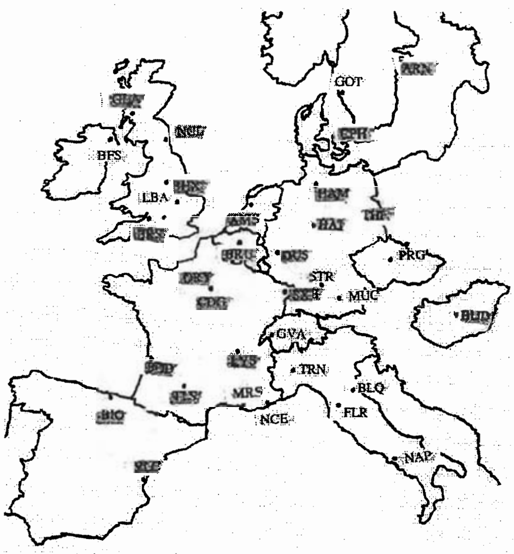

Table 7: Endogenous & Exogenous Delay Reasons at Turnaround

GOT	81 (89%)	72 (7%)	82 (3%)					
ARN	81 (50%)	88 (25%)	89 (25%)					
ORY	81 (39%)	72 (18%)	88 (16%)	89 (14%)	84 (8%)	98 (3%)	82 (2%)	
BIO	81 (72%)	72 (14%)	89 (14%)					
BHX	81 (65%)	89 (21%)	72 (6%)	88 (6%)	84 (1%)	51 (1%)		
CDG	88 (54%)	81 (20%)	72 (13%)	84 (7%)	82 (6%)			
HAJ	81 (29%)	84 (29%)	89 (24%)	72 (9%)	88 (9%)			
THF	81 (56%)	88 (20%)	72 (10%)	82 (5%)	85 (5%)	89 (4%)		
LBA	81 (67%)	88 (22%)	72 (8%)	89 (2%)	84 (1%)			
SXB	81 (75%)	88 (10%)	84 (9%)	83 (3%)	72 (3%)			
BRS	81 (42%)	88 (39%)	72 (7%)	83 (7%)	89 (2%)	77 (2%)	85 (1%)	
BFS	81 (92%)	89 (5%)	72 (3%)					
TLS	81 (42%)	89 (27%)	88 (13%)	72 (8%)	84 (5%)	82 (5%)		
CPH	81 (54%)	88 (21%)	89 (12%)	72 (6%)	84 (4%)	82 (2%)	85 (1%)	
BOD	81 (44%)	88 (23%)	89 (11%)	72 (9%)	98 (7%)	84 (4%)	71 (1%)	82 (1%)
DUS	88 (30%)	81 (26%)	82 (16%)	89 (12%)	72 (7%)	84 (7%)	85 (1%)	83 (1%)
NCL	81 (50%)	88 (39%)	72 (9%)	89 (2%)				
PRG	81 (66%)	88 (18%)	72 (8%)	89 (5%)	84 (2%)	82 (1%)		
AMS	89 (32%)	88 (28%)	81 (20%)	72 (11%)	82 (6%)	84 (2%)	71,98 (1%)	
MUC	81 (74%)	89 (18%)	82 (4%)	72 (3%)	84 (1%)			
STR	81 (46%)	88 (19%)	72 (14%)	89 (9%)	84 (6%)	82 (3%)	85 (2%)	98 (1%)
BUD	81 (90%)	89 (6%)	88 (2%)	83 (2%)				
GLA	81 (68%)	88 (17%)	72 (7%)	83 (5%)	85 (2%)	89 (1%)		
LYS	81 (78%)	89 (11%)	88 (5%)	72 (2%)	84 (2%)	82 (2%)		
HAM	82 (35%)	84 (24%)	81 (22%)	88 (11%)	89 (6%)	85 (2%)		
BLQ	81 (85%)	89 (7%)	88 (5%)	72 (3%)				
TRN	81 (85%)	89 (7%)	88 (5%)	72 (3%)	85 (0,5%)			
BRU	89 (46%)	81 (36%)	82 (9%)	88 (4%)	84 (3%)	85,83,72,73,77,51,71 (2%)		
MRS	81 (94%)	72 (3%)	88 (3%)					
FLR	81 (64%)	89 (21%)	72 (6%)	88 (6%)	85 (3%)	98 (0,3%)		
NCE	81 (54%)	89 (36%)	88 (4%)	84 (3%)	82 (3%)			
GVA	81 (77%)	72 (10%)	82 (10%)	84 (3%)				
NAP	81 (74%)	89 (12%)	72 (10%)	88 (4%)				
VLC	81 (78%)	89 (12%)	88 (8%)	72 (2%)				

Table 8: Main Exogenous Delay Reasons at Line Stations during Turnaround

2.5 Swapping

In an attempt to minimize the departure delay of flights in the network, *BelgoPunc* often decides to *swap* aircraft at the hub. In general, swapping of aircraft is performed if the actual arrival times and scheduled departure times are such that, with the aim of providing sufficient available turnaround time to each aircraft, it is advantageous to exchange the rotation among a set of carriers. In that respect, a swap involving 2 carriers would mean each aircraft continues the flight schedule of the *other* aircraft. It is clear that swapping imposes a great pressure on operational activities (e.g. crews have to be reassigned) and should only be carried as a last resort to resolve a punctuality problem. Frequent, recurrent swapping may also indicate flaws in the network design. As the following results suggest, swapping is far from an exceptional phenomenon at *BelgoPunc* and occurs regularly during the day:

rotations completed with 0 swaps	12,6%
rotations completed with 1 swaps	20,0%
rotations completed with 2 swaps	31,1%
rotations completed with 3 swaps	36,3%

Table 9: Swapping Behavior per Rotation

From table 9, it can be concluded that swapping occurs frequently. Only 12,6% of the aircraft finished their rotation without incurring a single swap. In 87,4% of the cases, at least one swap was carried out when the plane passed the hub. It is also striking that 36,3% of the rotations were swapped *each* time they visited Brussels, a phenomenon that may be partially explained by the so-called *alignment* policy in which swapped aircraft are re-swapped at their next transition at the hub mainly out of crew related reasons. The next table gives more details about the time when swapping is carried out.

rotations swapped in peak 1	64,5%
rotations swapped in peak 2	60,8%
rotations swapped in peak 3	72,3%

Table 10: Swapping Behavior per Peak

Table 10 is constructed looking at the 3 peaks of arrivals/departures in the hub (morning, afternoon and evening peak). Again, the figures displayed are remarkably high: in every peak, more than 60% of all the arriving aircraft were swapped! We will revisit the swapping strategy in paragraph 3.2.1 as we intend to model the swapping behavior in the simulation model.

2.6 Propagation

An interesting issue with respect to network punctuality concerns the matter of *propagation* of delay throughout a day. The issue of propagation boils down to the following question: "If an aircraft incurs a delay somewhere in its rotation during the day, will it then keep (or even increase) that delay at its subsequent flights in the day, or will it be able to catch up and be punctual again?". In order to address this issue, an adequate *measure* for propagation should be defined first. The measures that we used to define propagation are summarized in table 11. Each of the measures imposes some conditions that have to be fulfilled if a rotation is to be called a rotation with a propagation of delay. Carefully notice that cases that satisfy the conditions of the measure *OVERALL* also satisfy the conditions of the measures *DEPARTURE* and *DEPARTURE HUB*. Similarly, cases included in the *DEPARTURE* measure are also included in the *DEPARTURE HUB* measure.

MEASURE	CONDITION	COMMENT
OVERALL	delay at EMD DEP $\leq$ delay at BRU ARR_1 $\leq$ delay at BRU DEP_1 $\leq$ delay at BRU ARR_2 $\leq$ delay at BRU DEP_2 $\leq$ delay at BRU ARR_3 $\leq$ delay at BRU DEP_3	Both arrival and departure delays are taken into account.
DEPARTURE	delay at EMD DEP $\leq$ delay at BRU DEP_1 $\leq$ delay at BRU DEP_2 $\leq$ delay at BRU DEP_3	Only departure delays are taken into account.
DEPARTURE HUB	delay at BRU DEP_1 $\leq$ delay at BRU DEP_2 $\leq$ delay at BRU DEP_3	Only the departures in Brussels are taken into account.

Table 11: Delay Propagation Measures

First, we investigated those rotations of which we received data for all flights (no missing values) and in which no swaps occurred. In the entire summer 1999 schedule, there were only 328 rotations satisfying these conditions. Table 12 summarizes the results.

MEASURE	# of flights	%
OVERALL	2	0,6%
DEPARTURE	49	14,9%
DEPARTURE HUB	82	25,0%

Table 12: Delay Propagation Occurrence (no swaps)

For the flights that are included in table 12, we also calculated the correlation between departure delays across the several peaks in Brussels. The results are pictured in table 13.

	delay at EMD DEP	delay at BRU ARR_1	delay at BRU DEP_1	delay at BRU ARR_2	delay at BRU DEP_2	delay at BRU ARR_3	delay at BRU DEP_3
delay at EMD DEP	1	0.87	0.64	0.29	0.19	-0.01	-0.02
delay at BRU ARR_1		1	0.64	0.32	0.17	-0.04	-0.03
delay at BRU DEP_1			1	0.46	0.29	0.09	0.18
delay at BRU ARR_2				1	0.58	0.24	0.28
delay at BRU DEP_2					1	0.57	0.50
delay at BRU ARR_3						1	0.72
delay at BRU DEP_3							1

Table 13: Correlations between Delays

Second, we performed a similar analysis but we now also included rotations in which at least one swap occurred. Again, rotations with missing values were left out. This gave us at total 2672 rotations. Using the measures of table 11, we obtain the following results:

MEASURE	# of flights	%
OVERALL	4	0,2%
DEPARTURE	234	8,8%
DEPARTURE HUB	515	19,3%

Table 14: Delay Propagation Occurrence (at least 1 swap)

Again, we calculated correlations between delays at successive transitions at the hub. The results are shown in table 15. The major conclusions that can be drawn from tables 12 till 15 are:

- There is no evidence in the data that suggests delay is built up systematically during a day. Even for the least restrictive criterion, the percentage of rotations in which delay was accumulated is relatively low (around 20 to 25%).

- Looking at the correlation results, one can state that:
  - the impact of an *EMD* delay decreases through the day and has a moderate correlation (0.64) with the departure delay in Brussels in the first peak in case no swap is performed, and a negligible correlation (0.20) in case of swapping. It is safe to claim there are only little correlations with respect to the second and the third peak.
  - the impact of a *DEP* delay in a particular peak generally carries through one peak

only, t.i.: a late departure in one peak may cause a late arrival in the next peak, but not necessarily brings about a late departure in the next peak.

The conclusions from this paragraph are important as they suggest that peaks behave more or less *independently* from one another (looking at the departure punctuality). This is an important consideration to bear in mind when building the simulation model in part II as it simplifies the modelling of turnaround activities in a peak. It also confirms the frame of reference of figure 5 as the departure punctuality in a peak is most of all related to the arrival punctuality in the same peak. The results from this paragraph are an additional incentive to employ the framework of figure 5 as the base model for our simulation model.

	delay at EMD DEP	delay at BRU ARR_1	delay at BRU DEP_1	delay at BRU ARR_2	delay at BRU DEP_2	delay at BRU ARR_3	delay at BRU DEP_3
delay at EMD DEP	1	0.82	0.20	0.09	0.03	0.04	0.00
delay at BRU ARR_1		1	0.28	0.18	0.04	-0.03	0.01
delay at BRU DEP_1			1	0.68	0.22	0.06	0.08
delay at BRU ARR_2				1	0.32	0.11	0.08
delay at BRU DEP_2					1	0.63	0.22
delay at BRU ARR_3						1	0.29
delay at BRU DEP_3							1

Table 15: Correlations between Delays

Part II

Analyzing Punctuality Improvement Scenarios with Simulation

In part I, we extensively commented on the results of a punctuality study of *BelgoPunc's* network. At some places in our discussion, we also indicated the implications of certain results on the modelling choices that we have to make when building an adequate simulation model of *BelgoPunc's* network. It is the purpose of this second part of our research report to (1) give an overview of the logic behind our simulation model, (2) to discuss some implementation aspects and (3) to reflect on the simulation results of several punctuality improvement strategies.

3 Simulation Model

3.1 A Generic Line Station

From a global point of view, we modelled the turnaround activities of a line station as those of a simple server that handles incoming aircraft with a *flight number specific* service time distribution. This approach was followed because some of the outgoing flights at a line station are more inflicted with delays than others. In that respect, for every pair of incoming and outgoing flights that is scheduled to pass through a line station, we set up an individual service time distribution. Returning to figure 1 we would have a separate service time distribution for the flight pairs *(MA200,MA405)*, *(MA590,MA800)* and *(MA985,MA151)*. In addition, we let the turnaround performance of a line station depend on the *arrival situation* of the incoming aircraft. Let the pair (i, o) stand for an incoming flight i and an outgoing flight o. Three cases are identified: (1) the incoming plane is on time ($ATA_i \leq STA_i$), turnaround proceeds according to *normal* circumstances, (2) the incoming aircraft is late, but there is still sufficient time left for rotation ($STA_i < ATA_i \leq STD_o - NORM$), turnaround proceeds according to *agitated* circumstances and (3) the incoming plane has considerable delay such that there is normally insufficient time left to rotate the carrier in order to get the plane on time in the air for the next flight ($ATA_i > STD_o - NORM$), turnaround proceeds according to *rushed* circumstances. Depending on the situation, the turnaround performance at a line station is sampled from a different distribution. For cases (1) and (2), a service time is sampled from a distribution that is fitted on actual deviations from STD_o, hence on $ATD_o - STD_o$. In case (3), the service time is sampled from a distribution that is fitted on actual deviations from the target rotation time $NORM$, hence on $(ATD_o - ATA_i) - NORM$.

Notice carefully how the target for a line station is determined by the arrival situation of the incoming aircraft. In cases (1) and (2), the line station, if it operates adequately, should be able to put the carrier in the air *on time*, i.e. at STD_o. In case (3) however, because of the considerable arrival delay of the incoming flight, the line station is expected to perform a turnaround in a time span no more than the $NORM$, i.e. it should be able to put the carrier in the air before or on $ATA_i + NORM$.[5]

[5] In an initial research state, we came up with a multidimensional approach where service time depends

Once a service time is sampled from the appropriate distribution, one or two delay reasons (if necessary) have to be assigned to the outgoing flight. In that respect, we partitioned the time axis and fitted specific delay reason distributions in function of the magnitude of the delay. The total amount of delay is then simply divided between one or two delay reasons according to a sampled scheme of proportions. Although one could argue for some delay reasons a more sophisticated approach might be followed, we felt impeded by the *high level* at which data were available. Indeed, it is extremely complicated to correctly unravel from the format of our data model the processes that are behind the delays.[6]

3.2 The Hub

3.2.1 Hub Modelling & Swapping Algorithm

For modelling the hub, we followed more or less the same approach as for a line station. An additional peculiarity of the hub is that sometimes aircraft may be swapped with the intention to reduce the network delay (see also paragraph 2.5). Consider figure 1 again. Assume that *CAR_2* with flight number *MA590* is estimated to arrive at 8:50 (40 minutes delay at arrival) and that *CAR_3* with flight number *MA985* is estimated to arrive 10 minutes too early. Assume further that the airline company has set the *NORM* rotation time to be 30 minutes. In that case, it would be advantageous to swap *CAR_2* and *CAR_3* since the total deviation (undershoot) from the *NORM* for both aircraft is considerably smaller than when each of them would continue according to the schedule ($5m$ instead of $30m$).

Although it is clear that in the above example swapping is advantageous, this is not always obvious in practice. Swapping is a complex process that is carried out by a human being, taking into account factors such as available rotation time, crew flexibility, operational restrictions and many more. Incorporating this human behavior in a simulation model is extremely difficult (not to mention the policy of *aligning* that we briefly touched in paragraph 2.5). Therefore, our current simulation model implements an *optimistic* swapping strategy (in terms of deviations of available turnaround times from the *NORM*), without considering any crew or aircraft related constraints. The swapping algorithm boils down to the following. For every incoming aircraft that has just landed at the hub (let's call it the *swapper*), we check whether it has any "superfluous" *TAT* available. We define superfluous *TAT* as the amount of *TAT* that the aircraft has available in addition to the *NORM*. If the aircraft has an amount of superfluous *TAT*, it searches for an aircraft that is on its way to the hub and that is estimated to have a *TAT* that is less than the *NORM* (let's call this aircraft the *swappee*). For all incoming flights with a shortage in expected *TAT*, the model checks whether the combined undershoot in available *TAT* with respect to the *NORM* for both the swapper and the swappee can be reduced by performing a swap. Since there will

on $(\boldsymbol{i}, o)$ with $\boldsymbol{i}$ a vector of incoming flights. This allowed us to incorporate cross flight correlations at the service level. In combination with our approach to let the service time depend on the arriving time of the incoming flight, this quickly led to an explosion of the number of cases. In addition, the problem of selecting flights to be included in $\boldsymbol{i}$ made us withdraw from the approach.

[6]For some delay reasons, we managed to set up specific probability densities on the frequency of occurrence and the magnitude of the delay. We attempted then to compose a pair of delay reasons (as in the data model) by consecutively sampling from every delay reason density individually. This strategy however inflicted us with the problem of correctly (in terms of validity) aggregating the sampled *collection* of delays into a *pair* of delay reasons.

probably be more than 1 incoming aircraft with an estimated shortage in available *TAT*, the swapper searches for the incoming flight for which the greatest reduction in estimated *TAT* undershoot can be realized. If a tie occurs, the swap is performed with the aircraft that most urgently needs additional *TAT* (that had the greatest undershoot with respect to the *NORM*). Note that when a swap is carried out and the swappee arrives in the hub, the swappee becomes the swapper and the algorithm is executed in the same manner as explained above. This gives rise to the possibility of a swap that involves multiple aircraft, a common phenomenon that we also observed in *BelgoPunc's* network.

3.2.2 Spare Aircraft

An additional peculiarity of the hub is that sometimes *spare aircraft* may be used to resolve some of the delays. As *BelgoPunc* currently does not operate any spare aircraft, we cannot search the data to unravel a spare aircraft strategy that would closely fit its counterpart policy in the real world. We therefore let the policy of invoking a spare aircraft be controlled again by *estimates* of shortcomings in available rotation time, which are updated at the moment a flight is scheduled to arrive at the hub. In the same spirit as for the implementation of the swapping strategy, we followed an *optimistic* approach and assumed a perfect availability of the spare aircraft. This virtually implies spare aircraft have their engines running, waiting to instantly resolve a delay. Also, as soon as a carrier performing a rotation in which a spare aircraft is employed arrives at the hub, that carrier becomes a spare aircraft and may immediately be used to resolve other delays.

3.3 Validity & Simulation Goals

Validation is (in this case) all about creating confidence in the model results (see also [Kel00]). One knows ahead of time that the simulation model and the real world will not have identical outputs. Any model acts as a simplification of reality. It is up to the model user to decide if the output of the model is to be considered trustworthy or not. In reflecting upon this, it is important to mark out the *goals* of the simulation study. In that respect, the simulation model is meant to aid in the evaluation of the impact of different factors on the network punctuality of *BelgoPunc*. These factors were set to:

- block time coverage
- scheduled turnaround time
- swapping
- spare aircraft
- turnaround performance

Hence, even if the model does not reflect the real world in full detail, it can still be used to compare the impact of the above factors on the punctuality of the network. To give an example: the model does not include the possibility of a morning strike that would likely reduce the available workforce and almost certainly affect the punctuality. However, if one is willing to see this type of event as not relevant for the purpose of the study (e.g. due to the fact the impact of a strike is likely to be more or less the same for all levels of the above factors), the model remains valid although it does not incorporate an event that might occur in the real world. Another example concerns the single or double runway configuration in Brussels. It is known that due to weather conditions, Brussels airport management sometimes decides to switch from double to single runway. Obviously, this has a vast impact on punctuality and also on the probability of weather related delay reasons (e.g. 72). Again, if one is willing to see this type of event as not relevant for the purpose of the study, the model remains valid although it does not incorporate an event that might occur in the real world.

4 Implementation

4.1 ARENA Modules & Templates

We choose for the ARENA simulation environment from Rockwell Automation Software[7] to construct a *template* for the construction and the evaluation of airline networks. A well-documented and extensive covering of the package can be found in [Kel98]. ARENA is a hierarchical, high-level general-purpose simulator based on the simulation language SIMAN. One of the powerful features of ARENA is the construction and the usage of self-made *modules*. These modules are in fact nothing else than elementary chunks of SIMAN code that are often needed in a simulation model. Typical examples include a *server* module, a *conveyor* module, a *transporter* module, a *queue* module, etc. Self-made interrelated modules can easily be grouped in a so-called *template* which can then be distributed among other ARENA users. In [Gov01] for example, we developed an ARENA template for the simulation of Ethernet networks.

4.2 Airline Template

4.2.1 Overview

With the Airline template, the user can construct a particular airline network containing an unlimited number of carriers, flights and line stations. The template provides in an automatic animation of flights, swapping activities, delays, etc at run time. At the present time, the most important modules of our Airline template consist of a *carrier* module, a *flight* module, a *line station* module, a *hub* module and a *network* module. Building a simulation model for a particular airline network boils down to adding as many carrier and flight modules as necessary, specifying elementary network information in the network module, creating a hub module and adding a line station module for every line station in the network. All these modules contain generic animation code which provides the enduser with an automatically generated animation at run time. The user interface of the modules allow for the definition of flights and connections, the specification of the fleet, the identification of swappable carriers and spare aircraft, etc. By way of illustration, figure 8 contains part of the user interfaces of the carrier module and the flight module.

[7] Rockwell recently acquired ARENA from Systems Modelling, see http://www.automation.rockwell.com.

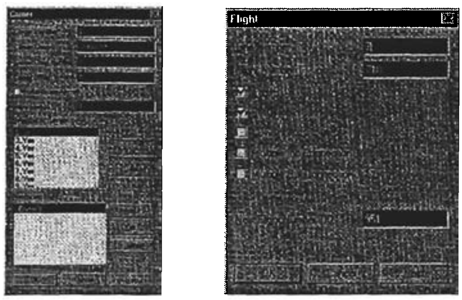

Figure 8: Carrier and Flight Module Interface

Since discussing the entire simulation logic would be out of the scope of this research report, we restrict ourselves in the following paragraphs to a number of selected topics.

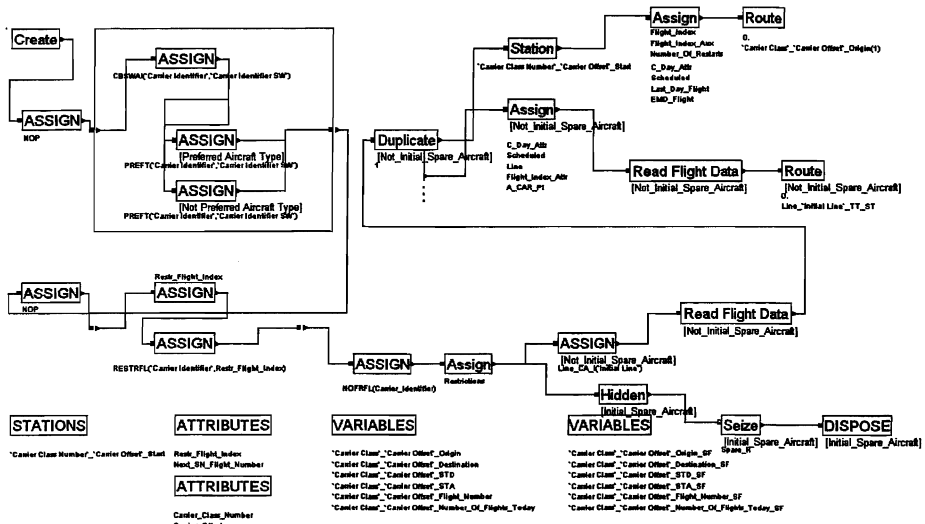

Figure 9: Carrier Module Logic

In figure 9, we placed an excerpt of the simulation logic that is behind the carrier module. For every carrier that is attached to the network, a set of logic as pictured in figure 9 is automatically added to the model. Technically speaking, we let in ARENA every carrier be represented by a simple entity that is routed through a sequence of stations. At the beginning of a simulation run, relevant time table data for each carrier is read from a file and stored in a variable structure.[8] Notice how we used *operands* from the carrier module to define this variable structure. In that respect, if a model builder specifies a carrier to be an AVRO85 type aircraft with identification number 1, the variable *'Carrier Name'_'Carrier Offset'_STD(i)*, containing the *STD* of the *i*th flight, will at compilation time be parsed into *AVRO85_1_STD(i)*. This not only allows for an unlimited number of carriers in the model, but it also gives us the opportunity to use meaningful filenames for storing carrier related time table data. Besides reading in time table information, we also set up a swap matrix that contains information about the carrier types and flights that may be swapped at the hub. If a carrier is properly initialized, it is put at the line station from which it will make its first flight.

Notice carefully that we deliberately choose to read in the network time table from file to make quick testing of alternative time tables possible without having to recompile the entire simulation model. As a matter of fact, compiling a simulation model containing 30 carriers and approximately 150 flights on a Pentium III 500Mhz system may well take over 3 hours of compilation time!

4.2.3 Flight Logic

Once a carrier arrives at an airport, an entire sequence of logic is executed that reads in turnaround performance data from the appropriate datafiles, delays the aircraft for some time, samples a block time from a distribution of block times and puts the carrier back in the air for its next flight. Since we mentioned yet earlier that the turnaround performance of a line station is a function of the pair of incoming and outgoing flights, we assembled the turnaround logic at the flight module instead of at the line station module (which may seem more appropriate at first sight).

The flight module contains also the animation logic for properly depicting the aircraft, visualizing the delay reasons, indicating whether an incoming aircraft is swapped, and many other things. When a model builder adds a flight module to his network, he will immediately have all the necessary storages, stations and routing lines for proper animation of the flight. Figure 10 contains an illustration of the animation objects that accompany a flight module. Similar to the carrier module, we used flight operands to define these animation objects, allowing an unlimited number of properly animated flights in a model.

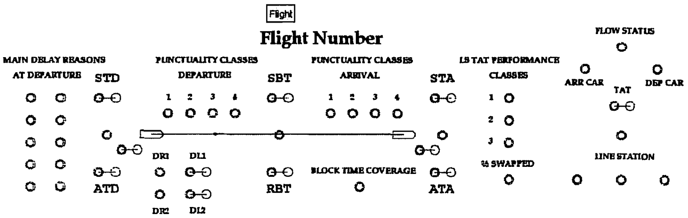

Figure 10: Flight Module Animation Objects

[8]We constructed a lower level template in ARENA that contains input related modules to read in time table data, flight delays, block time distributions, line station performance statistics, etc.

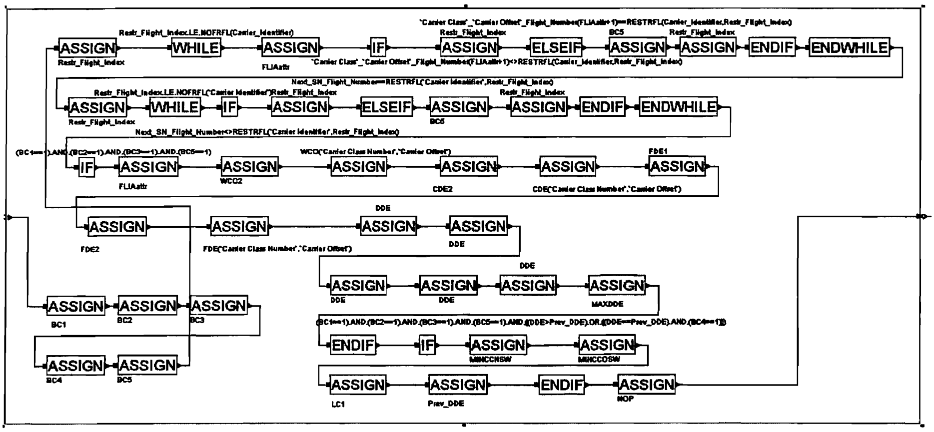

Figure 11: Repetitive Swapping Logic

4.2.4 Hub Logic

One of the advantages of a hub is the ability to swap aircraft if one is convinced this action might reduce the network delay. For every incoming plane at a hub, we check whether swapping the plane with one of the carriers that is heading for the hub would reduce the expected deviation from the *NORM* of the available turnaround times. We mentioned yet earlier that this kind of swapping strategy can be seen as an optimistic, constraint free swapping policy that attempts to get all available turnaround times as close to or above the *NORM.*

Since our Airline template allows for the simulation of any number of aircraft and flights, the swapping logic must be written such that it always scans the correct set of carriers and flights that are eligible for swapping. This is accomplished by using so-called *repetitive* logic in ARENA. Figure 11 illustrates this repetitive logic for the algorithm that determines the optimal swapping strategy for an incoming aircraft at the hub. First, in the interface of the hub module, the enduser will have to specify the carriers that pass the hub. Then, at compilation time, the logic of figure 11 will be generated and linked sequentially for every carrier that the model builder has identified in the interface of the hub module. This makes the swap determination algorithm a sequence of logic boxes where each box is of the form as pictured in figure 11. Finally, at run time, an incoming carrier will pass through this sequence of boxes, consecutively evaluating the outcome (in terms of deviations) of a possible swap with other carriers. This concept of *repetitive* logic is extremely powerful and we used it widely throughout our Airline template. An unfortunate side-effect however is the rapid explosion of SIMAN code and the inevitable increase in compilation time.

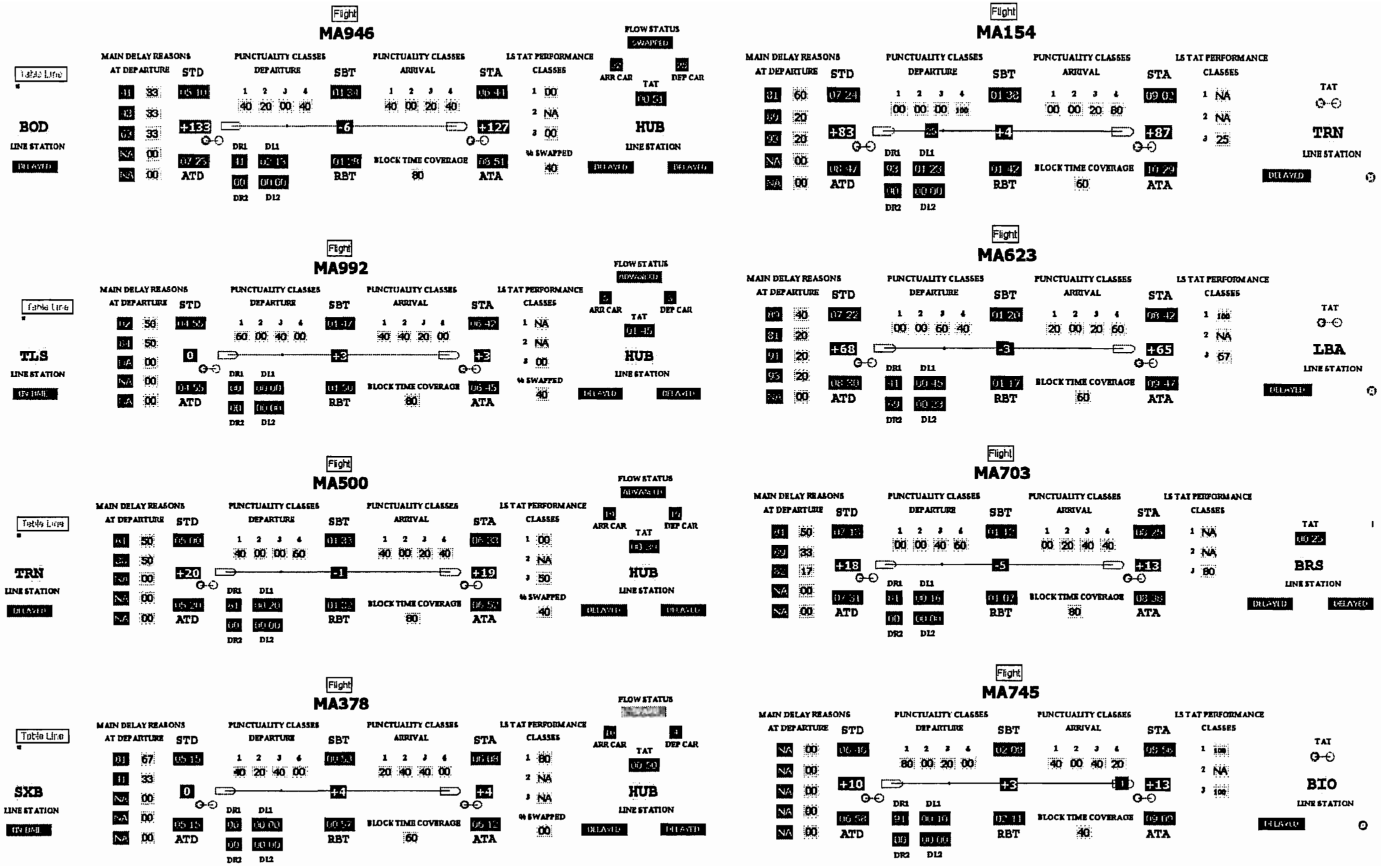

Figure 12: Network Animation and Flight Statistics

4.2.5 Animation & Output

In figure 12, we photographed a typical animation that may be obtained by running a model that is built with the Airline template. From the figure, we notice that flight *MA500* took off from *TRN* at 5:20 in the morning with a delay of 20 minutes, due to ATC Flow (delay code 81). The realized block time of the flight was slightly smaller than the published block time and the carrier arrived with a delay of 19 minutes at the hub. From there, we see that turnaround activities took 39 minutes leading to a delay at departure that is again attributed to ATC Flow. In about the same time frame, another incoming flight is facing a more severe delay. Flight *MA946* was subjected to technical problems at departure (delay code 41) and arrives with a total delay of more than 2 hours at the hub. For that reason, the hub decided to swap the incoming carrier (with number 22) with carrier 25 (which is not shown in the figure). Doing this, one managed to bring back the delay at departure of the next flight, *MA154*, to a level of 1h:23m. The departure delay is attributed to rotational delay (delay code 93). The figure also illustrates the use of a spare aircraft. Although flight *MA378* departed on time in *SXB*, its block time took longer than scheduled which causes the hub to invoke the spare aircraft for flight *MA745*.

In addition to animation, statistics are collected for every flight. For each flight, the most frequent delays are recorded, the punctuality at departure and arrival, the block time coverage, the swapping activities, etc. At the time the picture was taken, we see that flight *MA154* is mostly affected by the delay reasons 81, 89 (Local ATC) and 93. For flight *MA623*, we see it incurred in 40% of the cases a delay greater than 15 minutes (AEA threshold of delay). For each line station, we also keep track of the turnaround performance. For the line station *TRN*, which accepts *MA154* as an incoming flight, we notice the station managed to reach a good performance in only 25% of the cases. These cases are so-called type (3) cases as was explained in an earlier paragraph.

5 Simulation Results

In order to investigate the impact of published block time, aircraft turn around time, spare aircraft availability, aircraft swapping rules and different departure delay rates on the punctuality of the network, we have simulated a number of scenarios. In this section, we describe these scenarios and discuss the simulation results. As the simulation model provides in a lot of output data, we intend to restrict our discussion to a number of selected topics. The simulation results should enable us to come up with a *quantitative* estimate of the impact on the network punctuality of each of the factors under study.

5.1 Published BT & Scheduled TAT

5.1.1 Effect on Punctuality

In the airline industry, a common dispute in attempting to improve punctuality concerns the balance between *published block time* and *scheduled turnaround time*. Indeed, some airline companies advocate a tight network schedule with short grounding times but sufficient block times while others stick to the opposite strategy. In that respect, we wanted to investigate which of these factors is dominant concerning punctuality boosts. In that respect, we set the *BT* coverages at a constant level for all flights in the schedule. The levels that we simulated are positioned between the 50% percentile and the 90% percentile, with increments of 5%. Regarding the scheduled *TAT* factor, we wanted to investigate whether altering the scheduled *TATs* in the network has any effect on punctuality. For that purpose, we returned to the concept of the *NORM* (see paragraph 2.4.2) and set the scheduled *TAT* at a line station and the hub at values ranging from the *NORM* to the level of $NORM + 30$ with increments of 5.

For each combination of *BT* coverage and scheduled *TAT*, we ran the simulation for 100 days (equivalent to 100 independent observations). We also employed the well-known variance reduction technique *common random numbers* ([Kel00]) to reduce the effects of randomness in comparing the design points. Figure 13 indicates how the overall network punctuality evolves as the scheduled *TAT* and published *BT* change (we choose to employ the 15-minutes-delay norm because it appears that in practice this criterion is used more frequently than the 3-minutes-delay criterion).

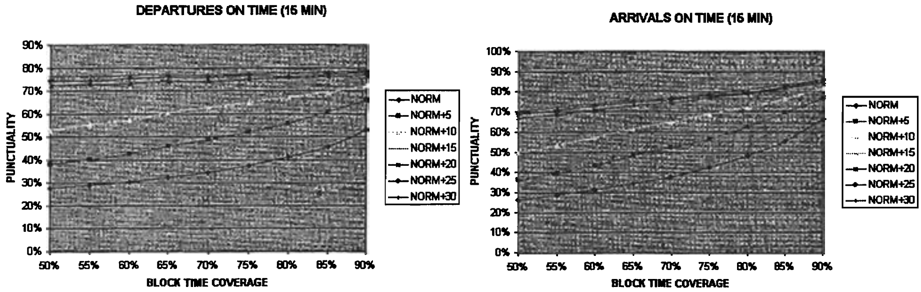

Figure 13: Departure & Arrival Punctuality

From the figure, it can be seen that both increasing the *BT* coverage and the scheduled *TAT* improves the overall network punctuality. However, if the scheduled *TAT* is already large ($> NORM + 15$), increasing the *BT* coverage will not result in a large effect on punctuality. On the other hand, for low values of the scheduled *TAT*, a large gain is achieved by changing the *BT* coverage, e.g. at $NORM + 5$, changing the *BT* coverage from 55% to 85% results in a 20% departure punctuality increase. Further, it can be seen that if the *BT* coverages are set at small values, large gains can be realized by giving the line stations more *TAT*. As the *BT* coverages go up, these gains get smaller. In that respect, the interaction between *BT* coverage and scheduled *TAT* are a nice illustration of the *law of diminishing returns.*

It is worth to mention that both an increase in *BT* coverage and scheduled *TAT* render the duration of a rotation longer (the rotation will have to start earlier or end later in the evening)! However, the typical S-shape form of a cumulative BT coverage distribution (like in figure 3) implies an increase from 55% to 85% in *BT* coverage causes only a minor increase in the block time (in terms of minutes). This suggests the *BT* coverage instrument is attractive for achieving considerable punctuality gain at only a small cost of increased scheduled block times. On the other hand, it is clear the instrument is limited as *BT* coverages above 90% imply significant block time increases and may render a rotation infeasible (as the rotation moves towards a time frame of more than 24 hours). In defense of the scheduled *TAT* instrument, one can certainly cite (1) commercial reasons (block times remain unchanged) and (2) a considerable boost in punctuality. However, increasing the scheduled TAT also means an increase in the ground time of aircraft, which inevitably raises operational costs. The marginal gains of these factors is further illustrated in figure 14.

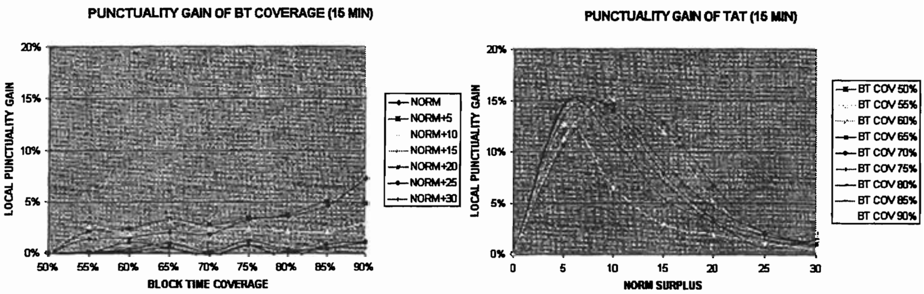

Figure 14: Departure & Arrival Punctuality Gain

Based on these graphs, one might conclude that changing the scheduled TAT offers more opportunities to boost network punctuality than changing the BT coverage. In terms of percentages, this is correct. However, as it generally takes few minutes to jump from one block time percentile to another, one should not underestimate the effect of changes in the BT coverage. As far as the punctuality gain of changing the TAT is concerned, it is interesting to note that each of the curves has a maximum. The maximum gain that can be achieved is positioned somewhere between $NORM + 5$ and $NORM + 15$ minutes. Note that the maximum is reached more quickly for smaller values of the BT coverage. As we mentioned already above: the smaller the BT coverage is, the larger the gains by increasing the scheduled TAT.

5.1.2 Other Effects

Rotational Delay What happens with the frequency of rotational delays (delay code 93) when the BT coverage and the scheduled TAT change? Figure 15 indicates one cannot completely prevent delay reason 93 from occurring by altering the level of these factors. Even when the scheduled TAT is set at $NORM + 30$ and the BT coverage is fixed at 90%, 15% of all delay reasons are still rotational delays!

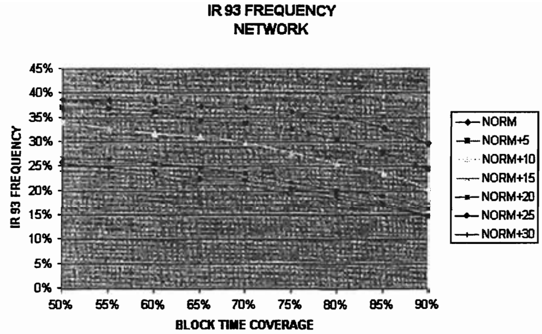

Figure 15: Rotational Delays as Function of BT Coverage and Scheduled TAT

Swapping The graph in figure 16 illustrates the swapping behavior in the network. It can be seen that if the *TAT* is at its lowest value, the percentage of swapped flights increases rapidly as the *BT* coverage increases. This is conform our expectations and results from the swapping rule that we implemented. Indeed, as the *BT* coverage climbs up, the number of aircraft that have "superfluous" turnaround time available to distribute to other aircraft rises. In that way, the figure shows the typical supply/demand behavior of a market in which a commodity (the *swap*) is exchanged. At a low value of both *BT* coverage and scheduled *TAT*, there is only little supply (only a few possible swappers) but large demand (many swappees). As the *BT* coverage increases, the number of possible *swappers* goes up, and given the high level of demand in the market, the number of exchanged goods rises (there will be a small drop in demand as the *BT* coverage increases, but this effect is negligible). This typical market behavior is reconfirmed when looking at the area in the figure where the *TAT* is at a high value (say $NORM + 20$). Indeed, the decline in the swapping rate as the *BT* coverage increases, indicates a (growing) overflow in supply. As the *BT* coverage goes up, the number of aircraft looking for a swapper goes down considerably and many former swappees are turned into possible swappers!

Instant Delay Propagation Figure 17 shows an instant delay multiplier statistic *(IDM)* at *BRU* for the different peaks. This instant delay multiplier is defined as (in the figures, the 3-minutes-delay criterion is used to define a delay at departure and at arrival): $IDM = \frac{\text{\%DELAYED\_DEPARTURES}}{\text{\%DELAYED\_ARRIVALS}}$. An instant delay multiplier > 1 indicates that a particular percentage of delayed arrivals at *BRU* is transformed into a *higher* percentage of delayed departures. This means that *BRU* "adds" delay to or "slows down" the network. An instant delay multiplier < 1 indicates that *BRU* is able to "absorb" a percentage of delayed arrivals and produces a lower rate of delayed departures. Looking at peak 1, we see that *BRU* adds a considerable delay to the network. This is largely due to the high rate of endogenous and exogenous delays that are caused by *BRU* in the first peak. Notice how the *IDM* increases when the *BT* coverage goes up. This can easily be explained since as the *BT* coverage goes up, the % of delayed arrivals will go down, a trend which not necessarily holds for the % of delayed departures since the latter is largely determined by the *TA* per-

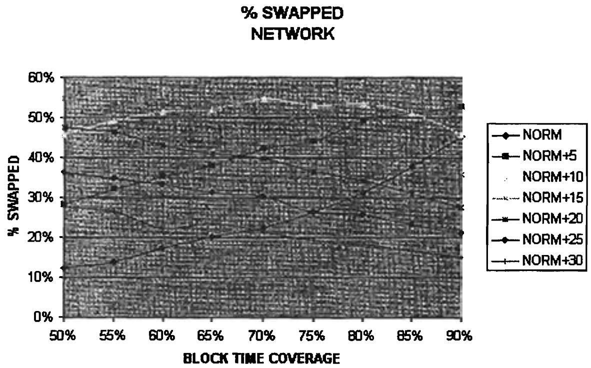

Figure 16: Swapping as Function of BT Coverage and Scheduled TAT

formance of *BRU*. Notice also the interaction between *BT* coverage and scheduled *TAT* in peaks 2 and 3 when looking at the *IDM*. For a low *BT* coverage, we see that increasing the scheduled *TAT* does not have a significant effect on the *IDM* (the *IDM* stays around 1.25). However, when the *BT* coverage is high, increasing the scheduled *TAT* boosts the *IDM*. This is an indication that at high levels of *BT* coverage, the reduction in arrival delays is greater than the reduction in departure delays when the scheduled *TAT* is increased.

5.2 Spare Aircraft

We mentioned yet before that one approach to improve network punctuality may be the deployment of spare aircraft in Brussels. Although this may seem a tempting solution at first sight to lift up punctuality, one should bear in mind it is an extremely costly solution and is also likely to have an effect on the frequency of *rotational* delays only (as spare aircraft are vulnerable to congestion and other delays like any other aircraft)! Figure 18 contains the results of simulating the network for the same combinations of *BT* coverage and scheduled *TAT* as in the previous section with respectively 1 and 2 spare aircraft available at the hub.

The table below may also help to clarify the effect of adding spares. The table is set up assuming that the *BTs* and the scheduled *TATs* were fixed to the values in the first column. The remaining columns give the simulated network punctuality and the gain of adding an extra spare aircraft.

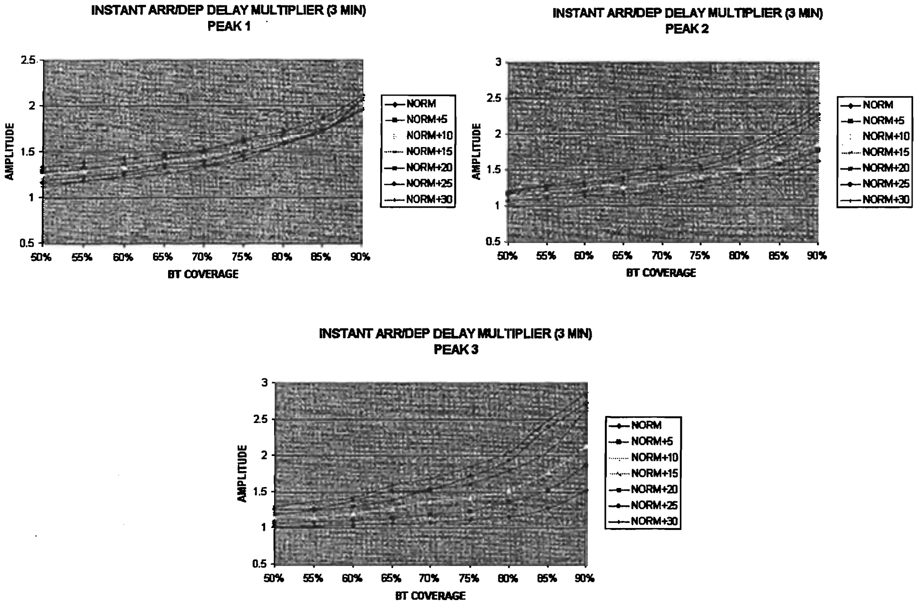

Figure 17: Delay Multipliers as Function of BT Coverage and Scheduled TAT

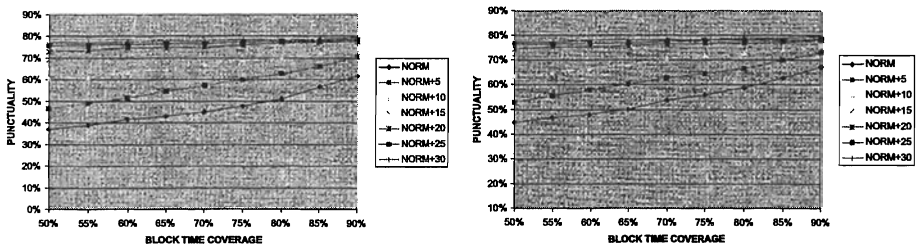

Figure 18: Spare Aircraft and Punctuality

	NO SPARE	1 SPARE	2 SPARES
BT 50%	53%	60%	63%
NORM + 10		(+ 7%)	(+3%)
BT 50%	73%	73%	75%
NORM + 20		(+ 0%)	(+ 2%)
BT 70%	63%	68%	71%
NORM + 10		(+ 5%)	(+ 3%)
BT 70%	74%	75%	76%
NORM + 20		(+ 1%)	(+ 1%)
BT 80%	67%	70%	73%
NORM + 10		(+ 3%)	(+ 3%)
BT 80%	76%	77%	77%
NORM + 20		(+ 1%)	(+ 0%)

Table 16: Summary of Spare Aircraft Benefits

It is safe to conclude from the table and the figures that adding spares does indeed improve the network punctuality though not drastically : the first spare yields about 3% (across the various design points), the second spare an additional 2%. In light of the improvements that can be achieved by altering the published *BT* or scheduled *TAT*, it is clear that adding spares is not a preferable strategy to bolster delay resilience.

5.3 Swapping Rules

We have learned yet from our data analysis in section 2.5 and from early simulation results that swapping occurs frequently. As swapping imposes a vast amount of workload and operational difficulties (e.g. reorganization of crew), it is interesting to find out how the schedule would perform if it was done without any form of swapping. In addition to shut down swapping completely, we also ran the simulation model with a slightly different set of swapping rules. Carefully analyzing the swapping rule of section 3.2.1, it is possible that a single large delay in the network is divided among multiple aircraft, a phenomenon one tries to avoid at all cost in practice as it is likely to turn *punctual* rotations into *delayed* rotations. The second set of swapping rules differs from the first in that the swapper will only perform a swap if that doesn't cause the available *TAT* of the swapper to pass an undershoot of 10 minutes with respect to the *NORM*.

Comparing figure 19 (left: no swapping; right: alternative swapping policy) with figure 13, it is surprising that the network punctuality doesn't seem to benefit that much from swapping. For some combinations of *BT* coverage and scheduled *TAT*, no swapping performs even slightly better than swapping!

5.4 Turnaround Performance

We know from part I that delay reasons are subdivided into three subsets: endogenous, exogenous and other reasons. In that respect, it is interesting to investigate what the overall gain in network punctuality would be if each line station manages to eliminate its endogenous delays (put differently: if each line station manages to refrain itself from violating the targets specified in a service level agreement with the airline company at the hub). Further, it is also interesting to see what would happen to the network punctuality if the exogenous delay reasons would be reduced. From a wide collection of possible simulation scenarios, we decided to pick out and to simulate the following cases ("perfect" stands for the absence of any form of exogenous or endogenous delay):

- Assuming peak 1 in Brussels is perfect
- Assuming peak 2 in Brussels is perfect
- Assuming peak 3 in Brussels is perfect
- Assuming peak 1 and 2 in Brussels are perfect
- Assuming peak 1, 2 and 3 in Brussels are perfect
- Leaving out all 81 and 89 reasons in Brussels only
- Leaving out all 81 and 89 reasons in all line stations
- Leaving out all endogenous reasons in all line stations
- Leaving out all endogenous reasons in Brussels only
- Leaving out all endogenous reasons in all line stations except Brussels
- Leaving out all exogenous reasons in all line stations
- Leaving out all exogenous reasons in Brussels only
- Leaving out all exogenous reasons in all line stations except Brussels
- Leaving out all exogenous and endogenous reasons in all line stations

The scenarios above were simulated on the original schedule of *BelgoPunc*, t.i. we left the scheduled *BTs* and *TATs* as they were specified originally by *BelgoPunc*. The following figures present the simulation results applying the 15-minutes-delay criterion. For means of comparison, we also included the results for the following simulations: (1) original schedule, (2) original schedule with 1 spare, (2) original schedule with 2 spares and (3) original schedule with no swaps.

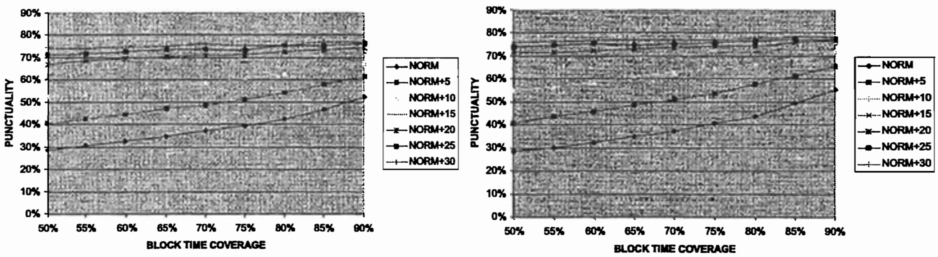

Figure 19: Swapping and Punctuality

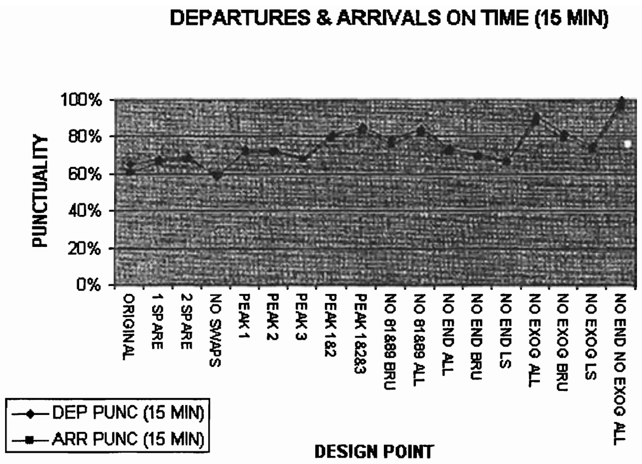

Figure 20: Departure & Arrival Punctuality under Alternative Scenarios

Figure 20 is interesting from a managerial point of view as it clearly indicates where opportunities for improvement are situated. In that respect, it provides an answer to the question: "What areas should investments focus on and what can be expected from these investments in terms of a punctuality gain?" From the figure, it is apparent that spare aircraft do not offer much in terms of network punctuality improvement (at most a 4% increase in departure punctuality is found). On the other hand, eliminating all exogenous delays in Brussels would really boost network punctuality (16% increase in departure punctuality, 18% increase in arrival punctuality). Hence, it seems that investments are better aimed at smart network design and congestion related improvements *(prevention)* than attempting to resolve delays with spare aircraft *(ex post reaction)*.

From figure 21 and 22, the same conclusions can be made. Additionally, the figures provide an answer to whether any carry-over effects are present from one peak to another. In case *BRU* manages to perform a faultless first peak, figure 21 tells us that the effects on the departure punctuality in peak 2 and 3 are small (compare PEAK 1 with ORIGINAL). Peak 2 behaves a bit better, but still the effect is small (+ 8%). However, the second graph indicates that the arrivals in the second peak are far more punctual (+ 16%). A similar conclusion can be drawn when peak 2 would be carried out without any exogenous or endogenous delays. Again (by comparison of PEAK 2 and ORIGINAL), we can see that the effects on peak 3 exist but are very small as far as departure punctuality is concerned (+ 3%). Again there are strong effects on the arrival punctuality in the third peak (+ 17%). This confirms nicely what we have discussed already in a previous section: there is *no propagation* of delay throughout the day. Delay carries over one peak only and the peaks in Brussels behave almost independently from one another. This has also an important managerial consequence. As a matter of fact, one of the typical paradigms that exist at *BelgoPunc* is that a perfect *early morning* peak guarantees a punctual day. From the figures, nothing is less true and *every* peak should be considered if one is to improve punctuality significantly! In that respect, a perfect behavior in Brussels at all peaks could drive up network punctuality with as much as 20% while perfect behavior in one peak only gives an increase of about 5 to 9%.

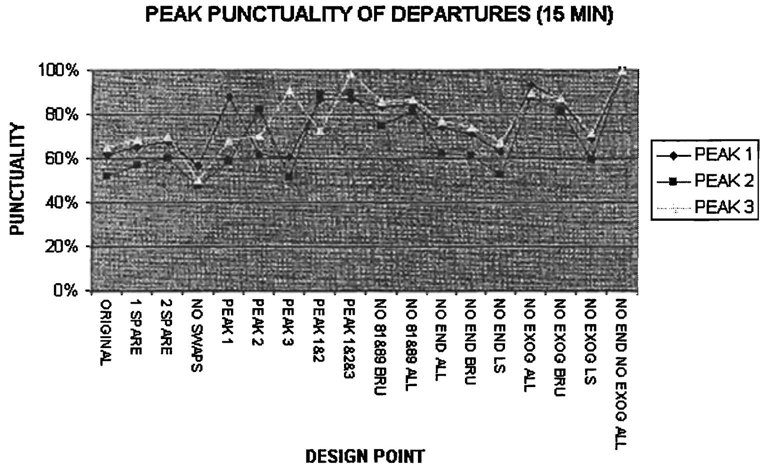

Figure 21: Departure Punctuality per Peak

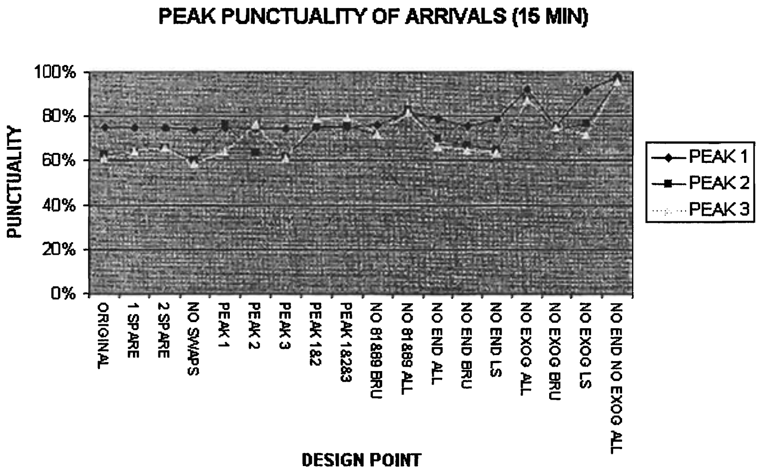

Figure 22: Arrival Punctuality per Peak

6 Conclusions

The simulation results in this research report indicate that the major opportunities to realize network punctuality gains are found in a reduction of exogenous delays. The importance of this kind of delays was already brought to light by our datastudy in part I and is reconfirmed by the simulation results in part II. Resolving endogenous delays also raises punctuality, though we found that resolving these delays has a smaller impact than eliminating exogenous delays. On the side of finding a solution to frequent rotational delays, we found that neither the use of spare aircraft, nor swapping provides in a significant punctuality boost. The conclusion that swapping does not significantly add to the punctuality of an airline's network may seem somewhat controversial at first sight, though one should bear in mind that swapped aircraft are also vulnerable themselves to both endogenous and exogenous delays. With regard to the design of a flight schedule, simulation results in this research report have shown the importance of scheduled TAT and published BT in search of sustainable punctuality improvements.

From the punctuality study that we presented in this report, many future research activities may come out. First, with respect to *BelgoPunc*, it is of interest to verify whether the same conclusions can be drawn if new data covering a different period would be provided. Another challenge is to extend the model so that it can deal with more components such as market related flight statistics, crew availability, fleet information and details on interconnected flights. This brings us to a possible long-term research project that is aimed at establishing a profound, interactive simulation environment that can be used by network designers to test particular network proposals, pinpoint bottleneck areas in the flight schedule, or even use simulation in real time to provide in a quantitative back up of certain managerial decisions.

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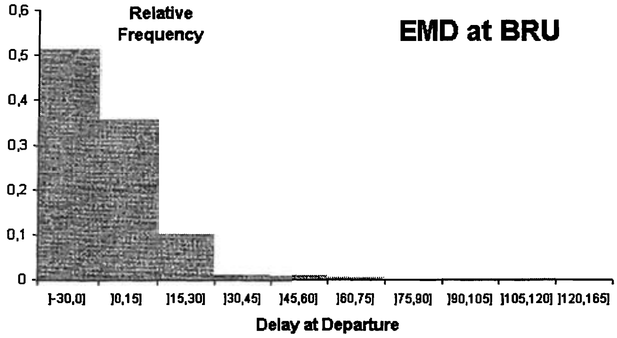
[Kel00] Law A. & Kelton W. (2000) *Simulation Modelling and Analysis*, McGraw-Hill.

Appendix

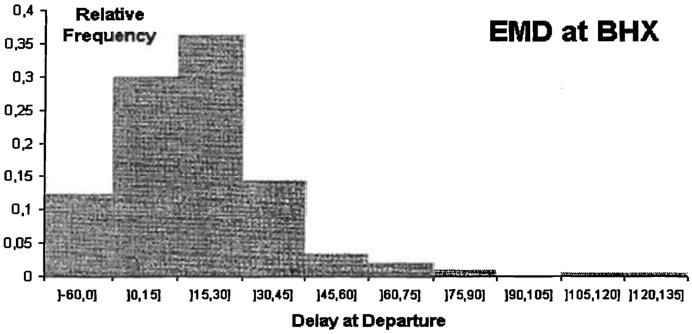
Code	Meaning	Code	Meaning
1	Bussing problems	52	Damage during ground operations
9	Sched. Groundtime less than min.	55	EDP - departure control
11	Late check-in after deadline	56	EDP Cargo preparation/documents
12	Late check-in/congestion EB	57	Flight Plans
13	Check in error pax and bags	58	Edp others
14	Oversales booking errors	61	Flight Plans documentation
15	Boarding discrepancies late pax	62	Operational Request fuel/load
16	Pax convenience	63	Late crew brd other than CNX SB
17	Catering order late/incorrect	64	PNM shortage waiting stand by
18	Baggage control	65	PNM special request non ops rqst
21	Cargo documentation error	66	Late PNC brd/other than CNX-SB
22	Cargo Late positioning	67	PNC shortage / Waiting stand by
23	Cargo late acceptance	68	PNC error/special rqst/non ops
24	Cargo/mail inadequate packing	69	Capt rqst for security check
25	Cargo/mail oversales resa error	71	Weather at departure station
26	Cargo/mail late preparation	72	Weather at destination station
27	Mail documentation packing	73	Weather en route or alternate
28	Mail late positioning	75	Deicing of aircraft
29	Mail late acceptance	76	Removal snow/ice/water/sand apt
31	Load control documentation	77	Ground handling impaired by weather
32	Loading unloading	81	ATFM due to ATC en-route
33	Loading equipment and/or staff	82	Security
34	Servicing equipment	83	Immigration
35	Aircraft cleaning	84	Airport facilities
36	Fueling defueling	85	Restrictions dep airport
37	Catering	87	No gate due own activity
38	ULD lack or unserviceability	88	Restrictions dest. Airport
39	Techn. Equipm. Or lack of staff	89	ATC local ground mouv. Control
41	Aircraft defects	91	Load connection psgr mail cargo
42	Maintenance late release	92	Through check in error pax/bag
43	Non-scheduled maintenance	93	Aircraft rotation
44	Spares and maintenance equip.	94	PNC rotation from another flt
45	AOG to be carried to other station	95	Crew rotation from another flt
46	Aircraft change due technical reason	96	Operations control
47	Lack of planned stand by aircraft	97	Industrial action own airline
48	Sched. Cabin version adjustments	98	Industrial action outside own airline
51	Damage during flight operations	99	Not elsewhere specified

Table 17: Delay Codes

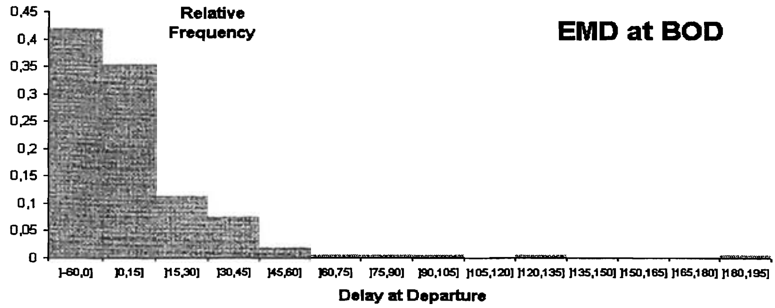
BRU (1630 observations)



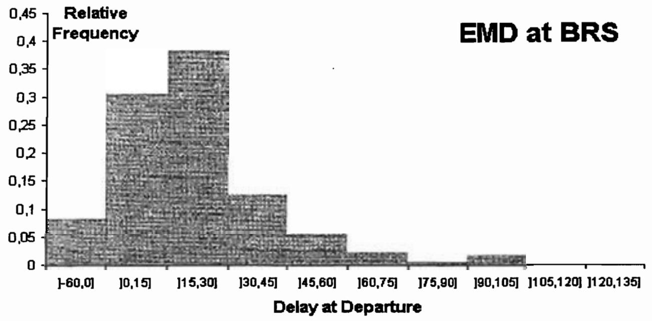
BHX (210 observations)



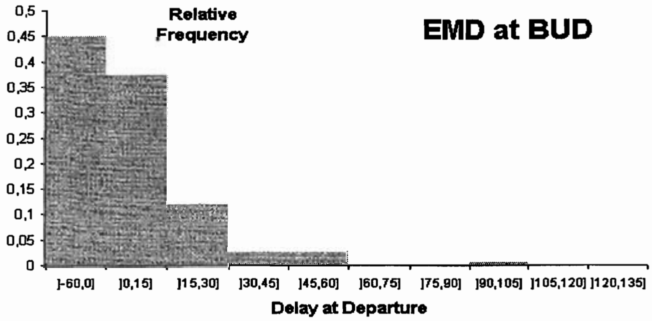
BOD (215 observations)



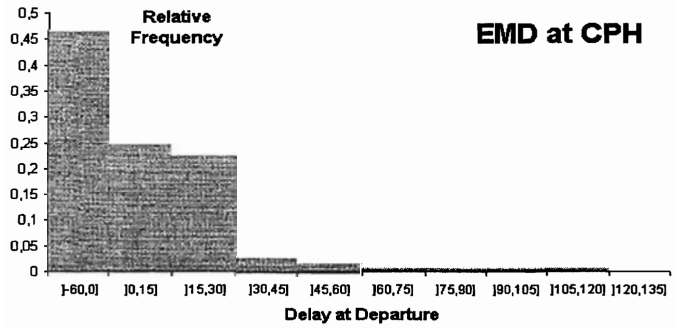
BRS (183 observations)



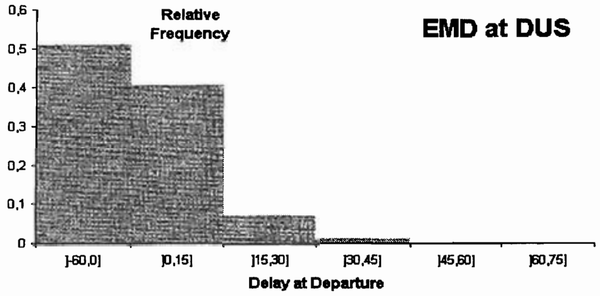
BUD (185 observations)



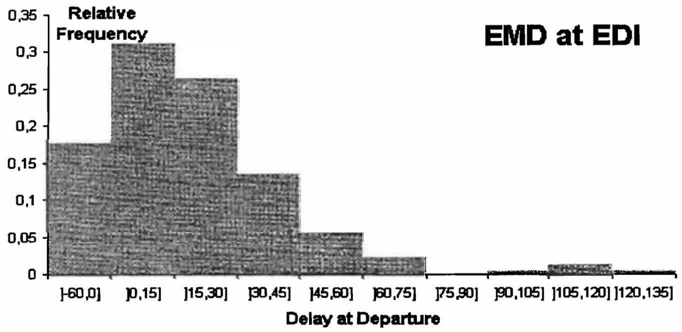
CPH (183 observations)



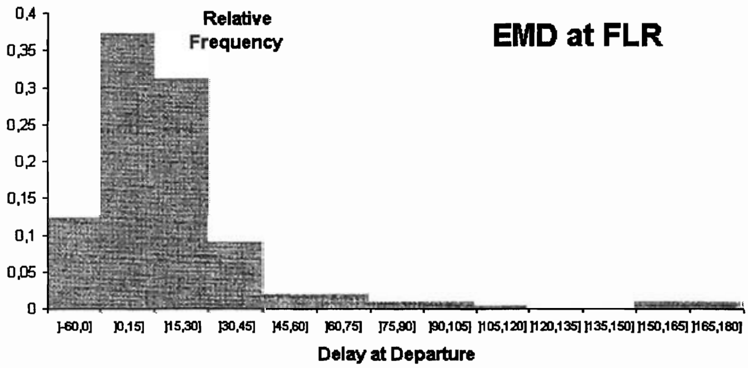
DUS (184 observations)



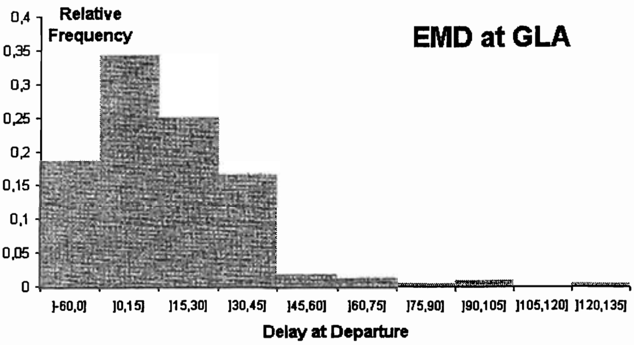
EDI (215 observations)



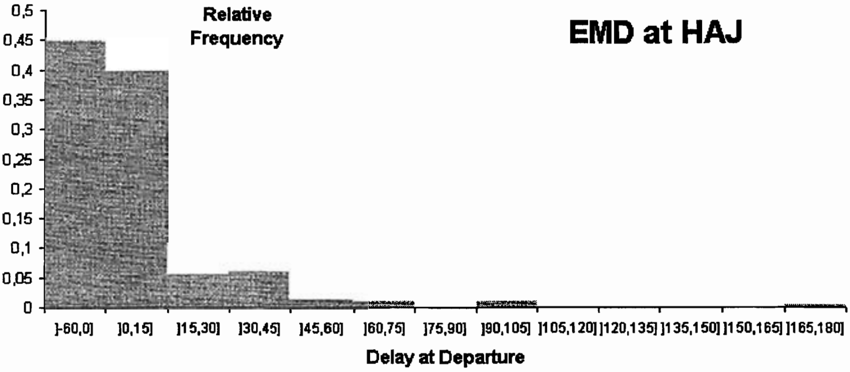
FLR (212 observations)



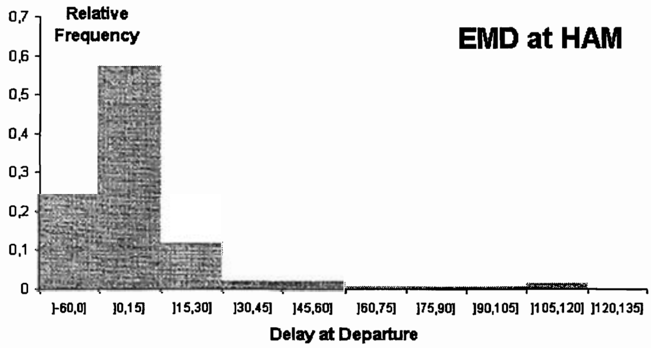
GLA (215 observations)



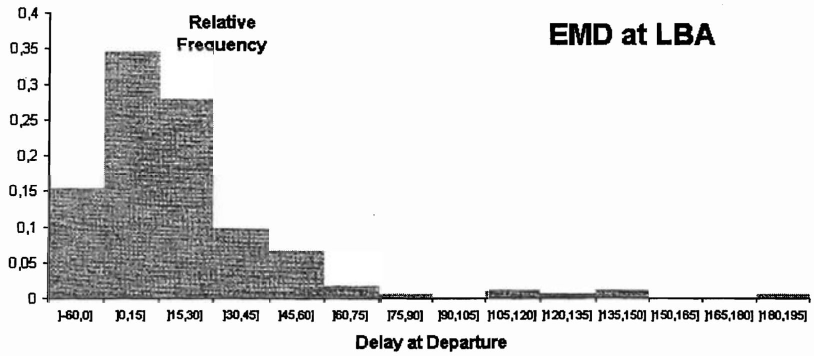
HAJ (216 observations)



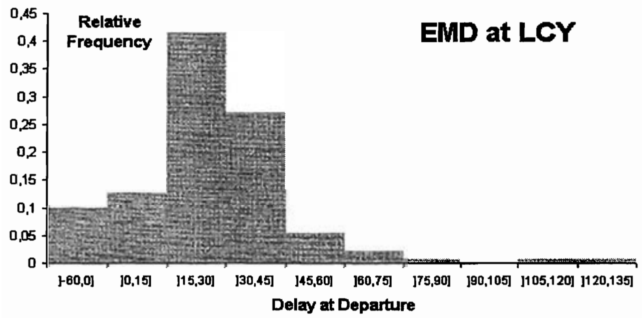
HAM (215 observations)



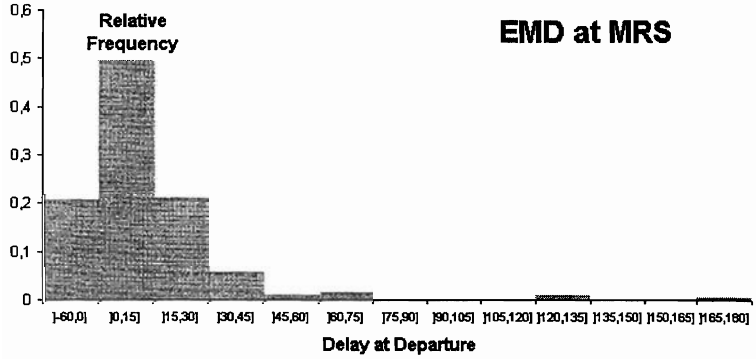
LBA (183 observations)



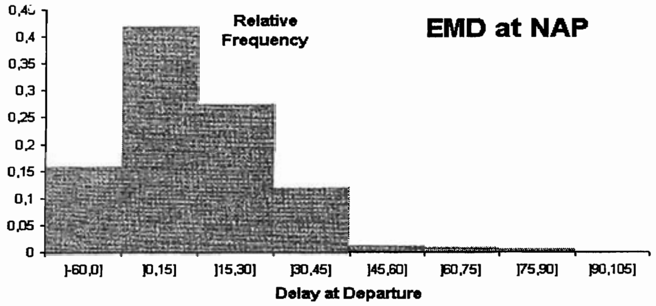
LCY (152 observations)



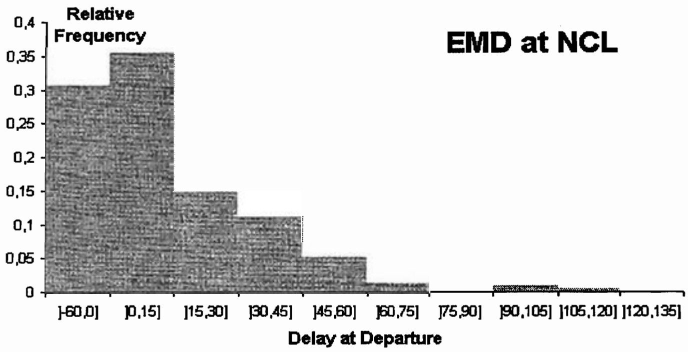
MRS (215 observations)



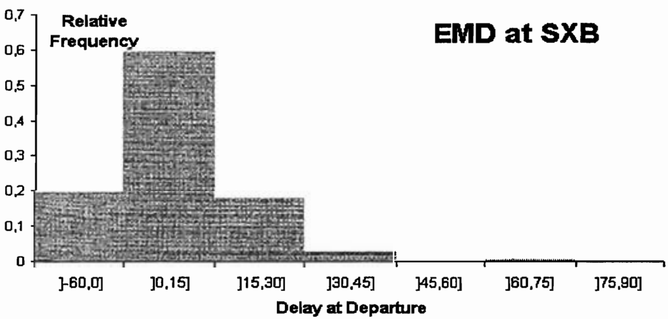
NAP (215 observations)



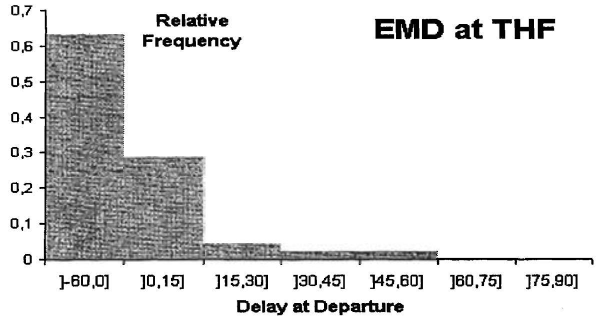
NCL (215 observations)



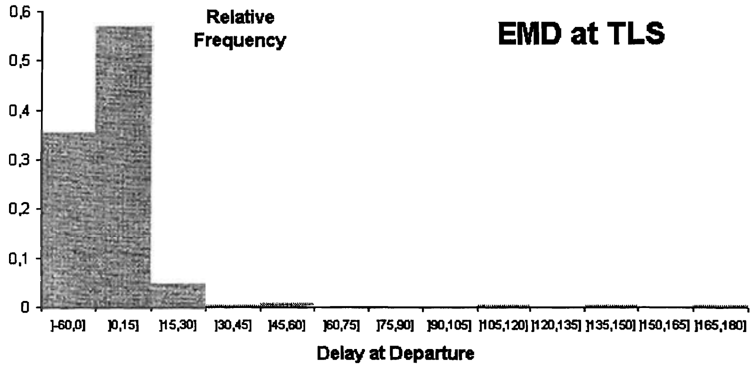
SXB (185 observations)



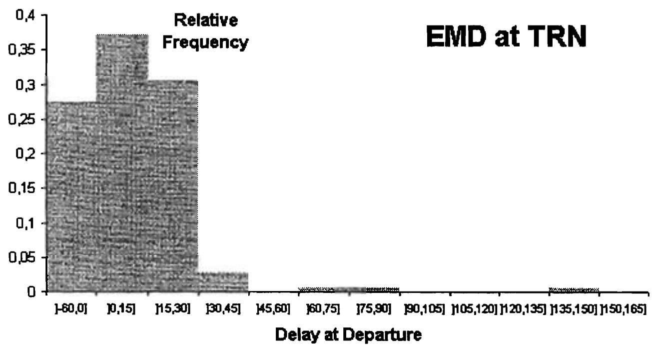
THF (49 observations)



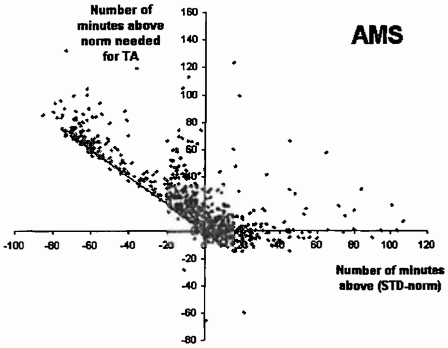
TLS (215 observations)



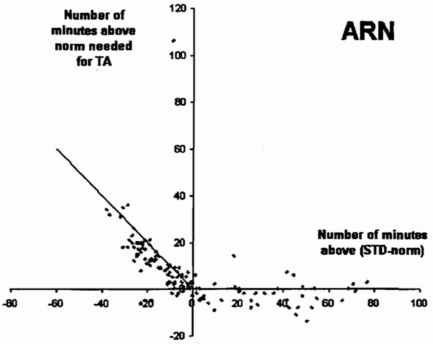
TRN (183 observations)



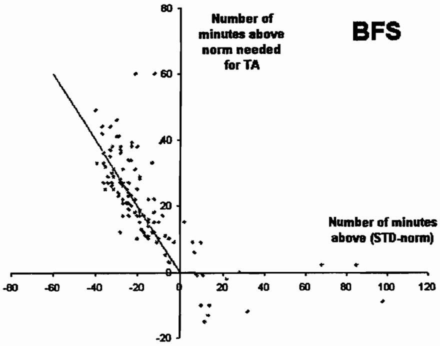
AMS (822 observations)



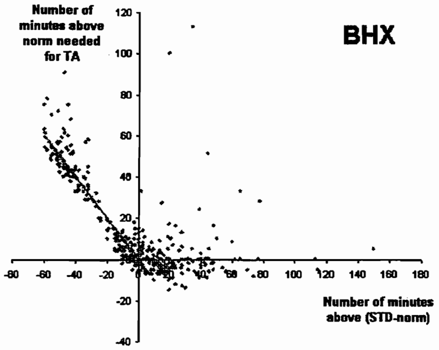
ARN (123 observations)



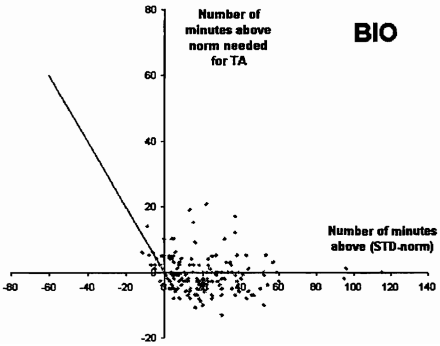
BFS (118 observations)



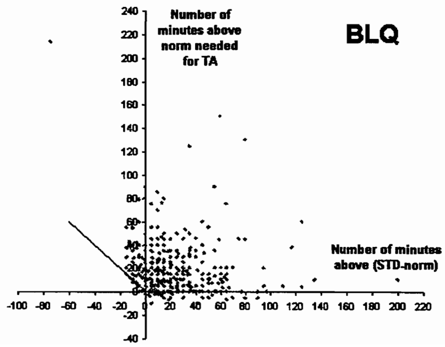
BHX (473 observations)



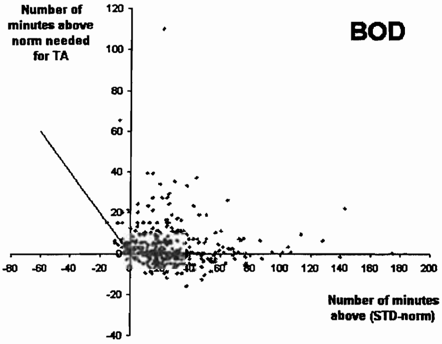
BIO (186 observations)



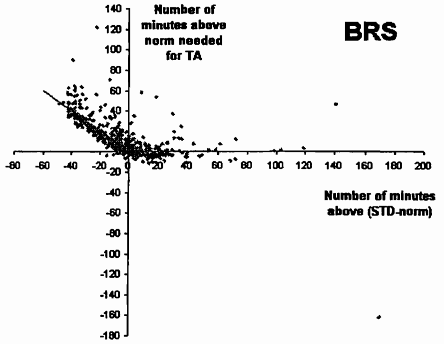
BLQ (398 observations)



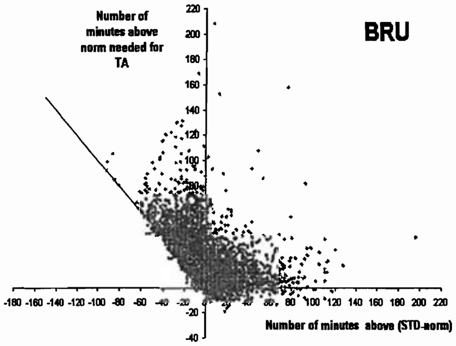
BOD (365 observations)



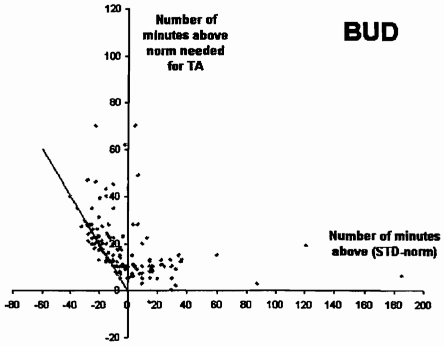
BRS (485 observations)



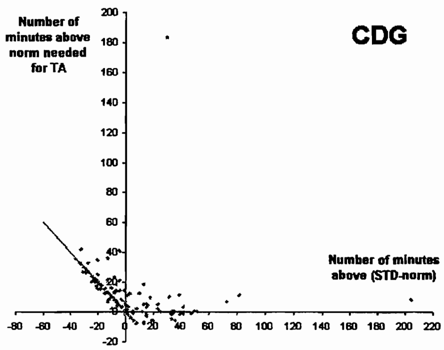
BRU (5568 observations)



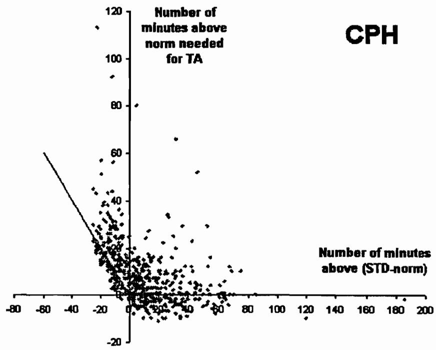
BUD (161 observations)



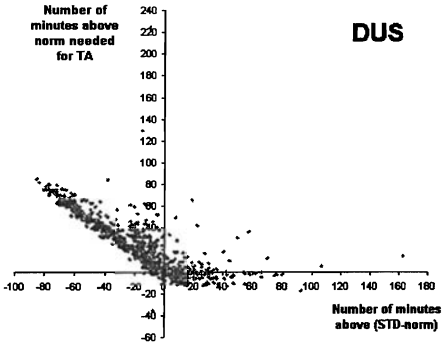
CDG (138 observations)



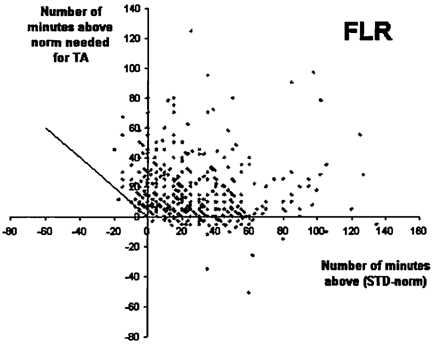
CPH (706 observations)



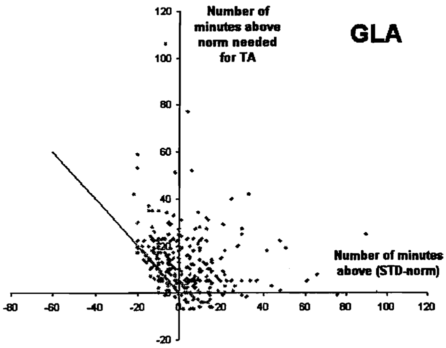
DUS (828 observations)



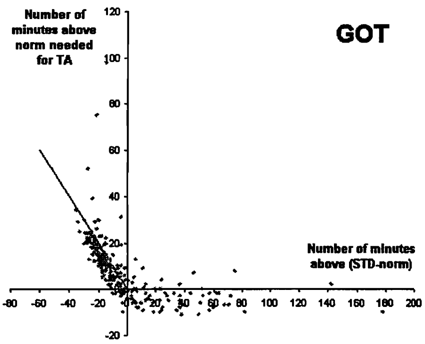
FLR (517 observations)



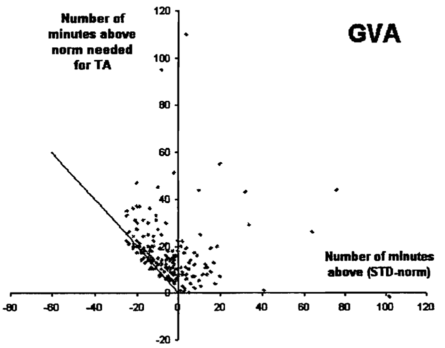
GLA (363 observations)



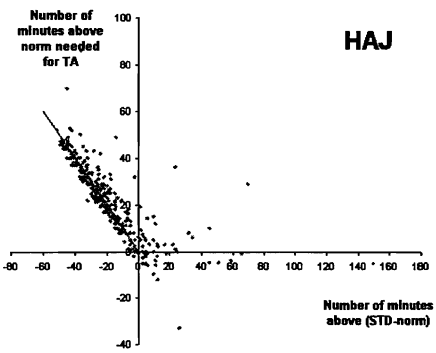
GOT (252 observations)



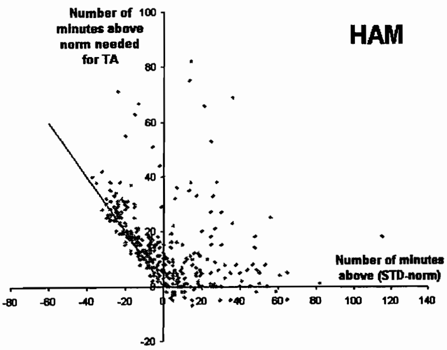
GVA (215 observations)



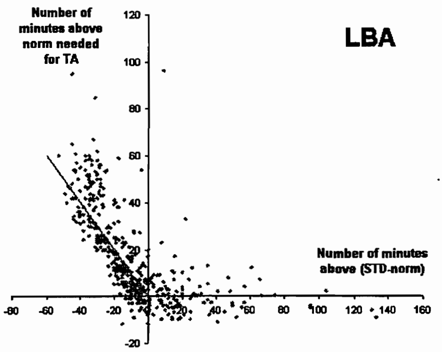
HAJ (371 observations)



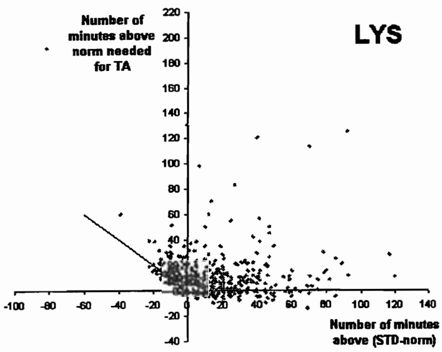
HAM (369 observations)



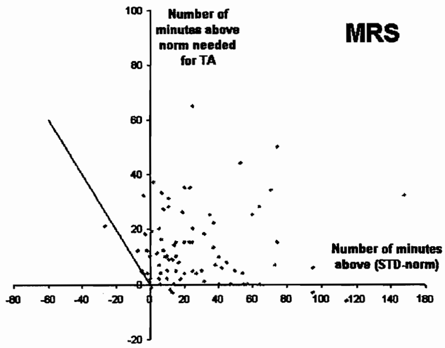
LBA (483 observations)



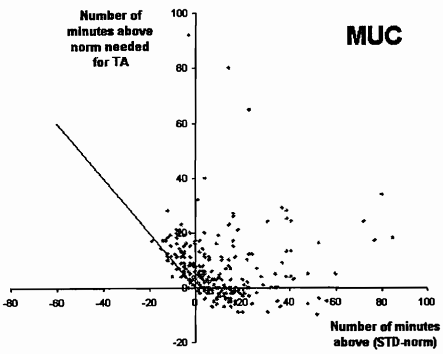
LYS (515 observations)



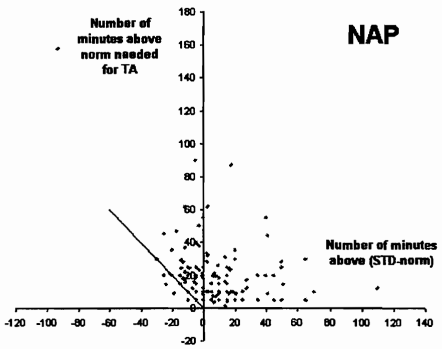
MRS (83 observations)



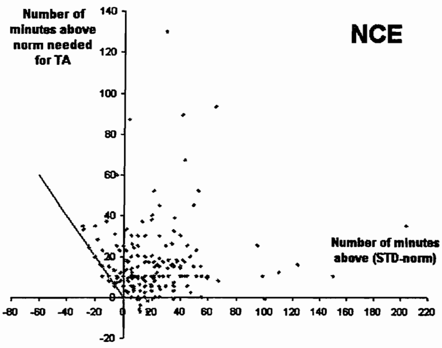
MUC (257 observations)



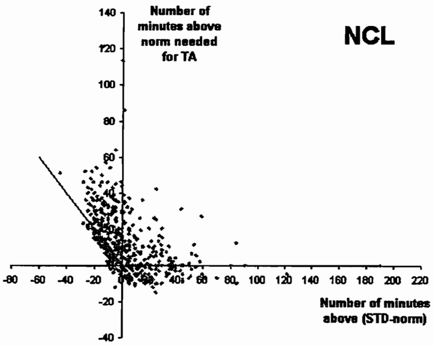
NAP (153 observations)



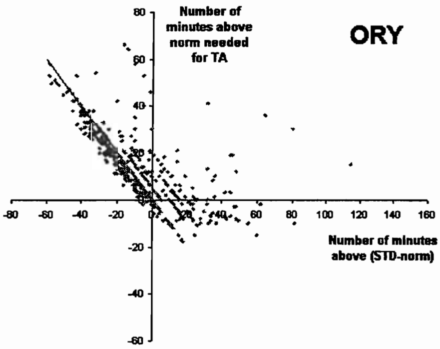
NCE (208 observations)



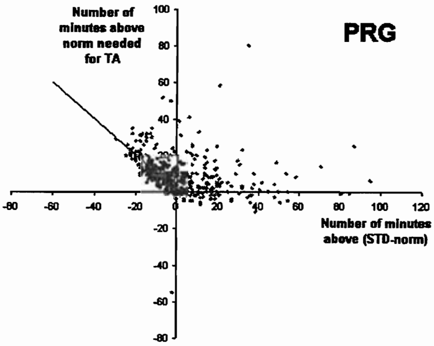
NCL (496 observations)



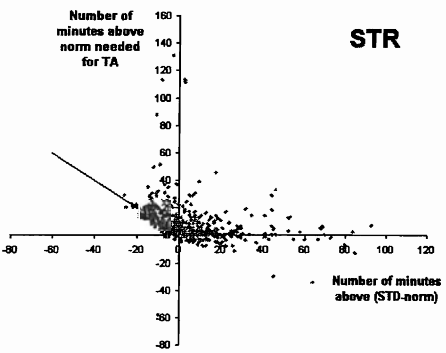
ORY (517 observations)



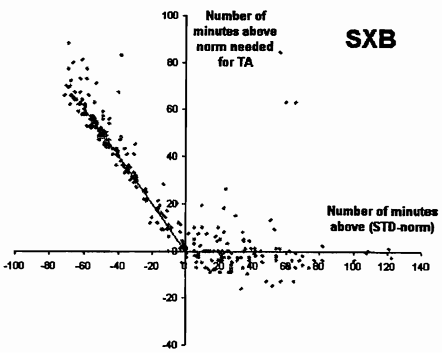
PRG (433 observations)



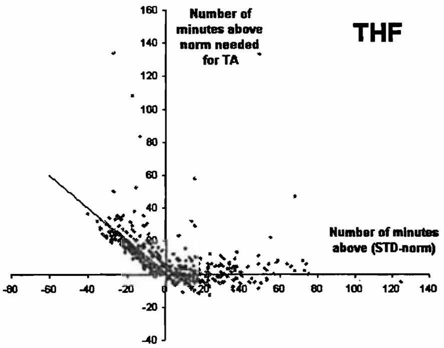
STR (497 observations)



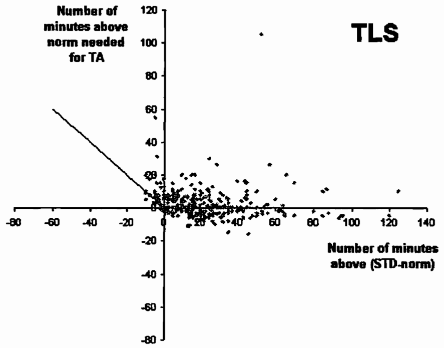
SXB (311 observations)



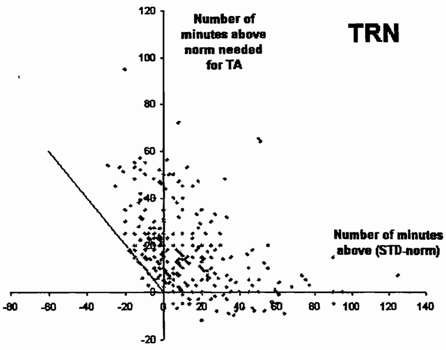
THF (520 observations)



TLS (366 observations)



TRN (333 observations)



VLC (215 observations)